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INVESTIGATION OF THE RF PROPERTIES OF CARBON FIBRE COMPOSITE MATERIALS

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FINAL REPORT

ERA Report No 81-109

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July 1982

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ABSTRACT

The resistivity of small CFC samples at frequencies up to 300 MHz was measured using Q-meter techniques. Values of 3-15 x 10^{-5} Ωm are typical at low frequencies and increase with increasing frequency indicating the presence of skin effect. Samples showed little change in their d.c. resistance as a result of prolonged exposure to various liquids although boiling in tap or sea water produced substantial increases in resistance.

Screening effectiveness to magnetic fields in the range 0.15 - 30 MHz and electric fields in the range 30 - 1000 MHz was measured for panels of CFC incorporated as one face of a copper cubic enclosure and as one surface panel of a Wessex helicopter tail cone. Screening effectiveness of a cylinder completely fabricated from CFC was also measured. Results indicate that the screening effectiveness of a CFC or part CFC fuselage, particularly in the hf band, will be critically dependent on the electrical continuity of bonds and joints and may be significantly less than for present day metal airframes. At vhf and uhf the screening effectiveness of part CFC and present day metal airframes are similar. The performances of vhf and uhf aerials when mounted on CFC or metal ground planes were similar and essentially within manufacturers' specifications.

Results of the investigations have been summarised and problem areas highlighted. The implications of these results on the EMC of CFC aircraft have been discussed and broad recommendations given. The report concludes with a survey of published work on the electrical and rf properties of CFC.

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FIBRES AND RESINS

Throughout this report various commercially-available fibres and resins are referred to in abbreviated form. Full details of these are :

1 Fibres

Abbreviated Title	Further Details	Supplier
Super A	Superseded by XAS	Courtaulds
HM (High Modulus)	-	"
XAS	130 SC/10000	"

2 Resins

Abbreviated Title	Further Details	Supplier
Code 69	-	Fothergill and Harvey
BSL 913	Low Temperature Cure	Ciba Geigy
BSL 914	High Temperature Cure	" "
BSL 916	-	" "
BSL 920	-	" "

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Chapter No

CHAPTER 1

INTRODUCTION

D A Bull and A McHale

CONTENTS

1 BACKGROUND TO THE INVESTIGATION

Since the invention of carbon fibre reinforced plastic (CFRP) by the Royal Aircraft Establishment, Farnborough in the 1950's work has been progressing steadily to determine the mechanical properties of the material. By the late 1960's the material was being considered for both primary and secondary structures in aircraft initially for weight saving but also because in the late 1970's and early 80's it would become more cost-effective to use such materials. This opinion was shared by many in the USA where, to confuse the issue, the material was known as epoxy-bonded graphite (EBG) or graphite reinforced plastic (GRP). The term now used in the UK to describe the range of composite materials that has been developed over the years is Carbon Fibre Composites (CFC). This is the term used in this report.

Some early research into certain electrical properties of CFC materials was undertaken in the UK during the period 1970-73; however this was insignificant in comparison with the research programme covering the mechanical aspects of the materials. Further investigation was therefore required to redress the balance and build up a sound understanding of the electrical properties of CFC at both d.c. and rf.

To assess the current position in terms of research into the electrical properties of CFC in the USA, ERA were sponsored, in part by ALS(IS)3*, MOD, to attend the IEEE International EMC Symposium in Washington DC during July 1976 (ref 1). Two papers directly relevant to the electromagnetic properties of CFC were given at this symposium (refs 2 and 3). These gave good insight into the research envisaged in the future. What became apparent from these papers and from subsequent discussions with workers at various establishments in the USA was that a unified definition of screening effectiveness required development together with techniques for obtaining experimental screening results.

* Air Electronic Systems (Installation and Support), since succeeded by A Rad 13e (within the Directorate of Aircraft Radio Systems).

A contract was awarded by ALS(IS)3, MOD to ERA in July 1977 for the study of resistivity and screening effectiveness of CFC. The results of this work are reported here.

2 DISCUSSION

The overall UK MOD(PE) research programme into the electrical properties of CFC, of which the ERA investigations formed a part, is described in reference 4. The ERA work, described in this report, included measurement of the following :-

a) The resistivity of small CFC samples at frequencies up to 300 MHz
b) The effect of various fluids on the d.c. resistance of small CFC samples
c) The electromagnetic screening properties of CFC materials, both for flat sheets of CFC incorporated as part of a copper enclosure and a helicopter tail cone and also for a cylindrical structure completely fabricated from CFC.
d) The performance of vhf and uhf aerials mounted on structures fabricated completely or in part from CFC.

Progress reports covering these aspects of the work were issued during the course of the ERA contract. These reports are now combined into this final document which supersedes the original report series. It has been necessary, in part, to rearrange the information into a technically more logical order than that which resulted from the original time sequence of issue. Table 1 of this chapter has therefore been included to correlate the chapters in this document with the original progress reports.

In much of this document electromagnetic screening and field strength results have been expressed in terms of decibel (dB) values. EMC engineers and others involved in rf technology are usually familiar with the dB scale; however for those involved in other disciplines this may not be so. An explanatory note on the dB scale has therefore been appended to this chapter.

3 ACKNOWLEDGEMENTS

The authors wish to acknowledge the help received during the course of this investigation. In particular, our thanks go to Mr D.B. Dawson (Directorate of Aircraft Radio Systems, MoD(PE), London) and Dr J.M. Thomson (Royal Aircraft Establishment, Farnborough) in their respective roles as policy and technical authorities. Our thanks also go to following establishments and companies for their advice and also in many cases for supplying the materials so necessary for the successful completion of the work : MoD(PE), Westland Helicopters Ltd, British Aerospace, Plessey Research (Caswell) Ltd and the Culham Lightning Studies Unit.

Table 1
Correlation of chapters in this document and the original progress reports

Chapter	Subject Matter	Original report number and issue date
1	Introduction	New
2	Resistivity	Part 3320/R/2(Final)-Sept 79
3	Effect of fluids on resistance	Part 3320/R/2 (Final)-Sept 79
4	Screening-cubic enclosure	3320/R/3 (Final)-Mar 81
5	Additional screening -cubic enclosure	3320/R/7-Oct 81
6	Screening- low conductivity panels	3320/R/4-May 81
7	Screening-Wessex airframe	3320/R/5;part 3320/R/6-Aug 81
8	Screening- CFC cylinder	Part 3320/R/8-Oct 81
9	Aerial performance	Part 3320/R/8-Oct 81 Part 3320/R/6-Aug 81
10	Implications	New
11	Literature survey	3320/R/1 (First Draft)-May 78 Addendum 1 -Oct 78 Addendum 2 -Dec 78 Addendum 3 -July 79 Plus additional papers
12	References	-

APPENDIX

The decibel (dB) scale

Since this report is intended for workers in a number of disciplines the following note on the decibel (dB) scale (which is extensively used in this report) has been included for the benefit of those not totally familiar with the use of this logarithmic scale.

Radio frequency field strength, depending on the proximity and power of the source, may vary from a few microvolts/metre for a weak communications signal to several hundred volts/metre close to a high power transmitter, ie a range of 10^8. In addition, electromagnetic screening is usually expressed as the ratio of two field strengths, measured outside and within the protected area and, depending on the effectiveness of the screen, this ratio can extend from unity to values exceeding 10^5. The logarithmic dB scale is used extensively in rf and related disciplines, particularly in EMC, to facilitate the handling of these large ranges of values.

The dB scale is essentially one of power ratio. Hence :

$$\text{power ratio (dB)} = 10 \log \frac{P_2}{P_1}$$

Under constant impedance conditions this ratio can also be expressed in terms of voltage or current.

$$\text{power ratio (dB)} = 10 \log \frac{P_2}{P_1} = 20 \log \frac{V_2}{V_1} \text{ or } 20 \log \frac{I_2}{I_1}$$

In EMC, it is convenient to express radiated and conducted signals in terms of dB relative to a standard level. For example, when considering electric field strength a reference of 1 μV/m is normally used. A field strength of 200 mV/m expressed in dB relative to the 1 μV/m reference is then $20 \log \frac{200 \text{ mV/m}}{1\ \mu\text{V/m}} = 106 \text{ dB}(\mu\text{V/m})$

Screening is treated in a similar manner. If the field strengths outside and within a screened area are, say, 600 mV/m and 30 mV/m respectively then the screening value is given by $20 \log \frac{600 \text{ mV/m}}{30 \text{ mV/m}} = 26$ dB

Also from knowledge of the screening the field strength within a protected area is simply calculated when both the external field and the screening values are known in dB, eg for a 200 mV/m signal external to the above screened area the field in the protected area would be 106 dB(μV/m) - 26 dB = 80 dB(μV/m).

A common misunderstanding occurs when considering screening results plotted on a dB scale. Differences of 10 dB between results may appear to be small in comparison with screening values of say, 40 - 50 dB; however this 10 dB difference represents a ratio of 3.2 to 1.

Table A is a reference chart of dB values for use when converting field strength and screening values to and from dB. For example, from the Table A, 200 mV/m is 2×10^5 μV/m = 6 + 100 dB(μV/m)
= 106 dB(μV/m)

Also from the table 34 dB screening gives a reduction in field strength of 40 - 6 dB = 100 ÷ 2 = 50 times.

Table A. Decibel (dB) scale conversion chart for field strength and screening measurements

- ve	dB	+ ve	-ve	dB	+ve
0.89	1	1.12	0.20	14	5.01
0.79	2	1.26	0.18	15	5.62
0.71	3	1.41	0.16	16	6.31
0.63	4	1.59	0.14	17	7.08
0.56	5	1.78	0.13	18	7.94
0.50	6	2.00	0.11	19	8.91
0.45	7	2.24	0.10	20	10.0
0.40	8	2.51			
0.35	9	2.82	10^{-2}	40	10^{2}
0.32	10	3.16	10^{-3}	60	10^{3}
0.28	11	3.55	10^{-4}	80	10^{4}
0.25	12	3.98	10^{-5}	100	10^{5}
0.22	13	4.47	10^{-6}	120	10^{6}

CHAPTER 2

MEASUREMENTS OF RESISTIVITY OF CARBON FIBRE COMPOSITE MATERIALS

B W Smithers

SUMMARY

Measurement techniques are described and results obtained for ten CFC materials at frequencies up to 300 MHz. Resistivity at d.c. and frequencies below 1 MHz generally lies in the range $3 - 15 \times 10^{-5}\ \Omega m$. Above 1 MHz the resistivity increases with increasing frequency due to skin effect. The resistivity of unidirectional materials, measured at directions perpendicular to the fibre lay is some two orders of magnitude greater than values measured both parallel to the fibre lay and also for other CFC materials.

CONTENTS

1 INTRODUCTION

This chapter describes measurements of resistivity of CFC materials at frequencies up to 300 MHz using 'Q' meter and vector impedance meter techniques.

Measurements of low-frequency conductivity (d.c. to 1 MHz) have been reported by Scruggs and Gajda (Ref.5) for current flow parallel or perpendicular to fibre direction in a unidirectional CFC material. Contact was made to opposite edges of rectangular samples by vacuum evaporation of aluminium. A thick coating of conductive paint was applied to the aluminium layer to prevent scratching of these surfaces.

At d.c. the voltage drop across the specimen was measured with a potentiometer, and an electrometer was used to measure current. At rf an oscilloscope and sampling resistor allowed voltage and current to be determined. The sample was composed of an unstated number of single plies containing Thornel T300 carbon fibres. No variation of conductivity from d.c. to 1 MHz was detected.

The method described above is unlikely to be adequate at frequencies above 1 MHz, as sample impedance is being measured rather than resistance, and in a 16 ply sample of the size indicated, inductive reactance could result in impedance exceeding resistance by 20% at 1 MHz.

Scruggs and Gajda note that Walker and Heintz (Ref.6) have found similar values of resistivity at 2 GHz to those at 1 MHz. Walker and Heintz describe some measurements using a CFC sample as a partition across an enlarged section of a 50 Ω line. Reflection and attenuation can be related to conductivity. Edge connection without leakage around the sample is difficult to ensure and with the radial E-field which arises analysis may prove impossible.

A strip-line method is also described where the test sample provides a shunt path which may be treated as a lumped impedance. Accuracy depends upon the accuracy of the circuit model and the authors look upon the resistive values with some suspicion especially above 1 GHz. Ignoring contact resistance a resistivity, ρ, of 1.0×10^{-3} Ωm was obtained from 100 MHz to 1000 MHz.

Another method used by Walker and Heintz incorporates CFC material (unidirectional) as part of a strip-line. When a number of conditions are satisfied, for example, sample thickness substantially greater than skin depth, a voltage standing wave pattern obtained by probes allows the computation of propagation constant and hence conductivity σ. Approximate values for resistivity of CFC were shown to be:

$$1.2 \times 10^{-5}\ \Omega\text{m at 1 GHz}$$

$$4.5 \times 10^{-5}\ \Omega\text{m at 2 GHz}$$

The method does not lend itself to frequencies much lower than those quoted.

Measurements made at ERA and described below used a Q-meter to obtain rf resistivity of small samples within the frequency range 1 MHz to 300 MHz.

A Hewlett-Packard vector impedance meter, Type 4815A, was used to measure complex impedance over the range 0.5 MHz to 108 MHz but was found to be limited in performance for low-resistance samples. Some measurements are, however, described below where the 4815A instrument was used for the measurement of a larger sample of somewhat higher resistance mounted in a transmission line. For comparison, measurements were also made on this sample using the Q-meter but the sample size limited the maximum frequency to 80 MHz.

2 TEST METHODS

2.1 Q-meter

The measurement of low value rf resistance (typical for small CFC samples) is accomplished by including the sample in series connection in a resonant circuit as indicated in Fig.1. Figure 2 shows the test jig used at frequencies of 50 MHz and below. For frequencies between 100 MHz and 300 MHz shorter connections are required and Fig.3 shows a standard inductor and inductor with test sample included.

In the jig shown in Fig.2, if:

Q_1 = Q value obtained with the test sample shorted

Q_2 = Q value obtained with the test sample in circuit

and C_1 and C_2 are the corresponding indicated values of tuning capacitance for resonance then:

$$R_x = \frac{1}{\omega} \cdot \left[\frac{1}{C_2\ Q_2} - \frac{1}{C_1\ Q_1} \right]$$

where R_x is the required value of resistance of the test sample.

The effective series capacitance C_x of the sample is also obtainable and is given by:

$$C_x = \frac{C_1\ C_2}{C_2 - C_1}$$

All tests were conducted at room temperature and prevailing humidity conditions.

Additionally, resistance under direct current conditions was obtained at a current of 200 mA.

2.2 Vector impedance meter

A sample forming the inner conductor of a parallel-plate line was short-circuited at one end. The impedance at the open end was measured at frequencies up to 100 MHz by means of a Hewlett-Packard vector impedance meter, and the sample resistance calculated. This sample was also examined by the Q-meter method but sample size limited the maximum test frequency to 80 MHz.

When using the vector impedance meter for this low resistance sample (0.18 Ω d.c.), the lowest meter range being 10 Ω f.s.d., it was found necessary to minimise errors by adopting the following procedure:

(a) The impedance meter probe was inserted in the '100 Ω probe-check' socket on the front panel and the 'magnitude adjust' and 'phase zero' controls were adjusted to read 100 Ω and 0° on their respective meters at each test frequency.

(b) The probe tip was short-circuited and the magnitude and phase angle meter reading noted.

(c) The probe was attached to the sample and the magnitude and phase reading obtained.

(d) The difference between the resistive terms computed in (b) and (c) gave the resistance of the sample.

3 PREPARATION OF CFC SAMPLES

Ten sheets of CFC material were supplied, nine by British Aerospace (Warton) and one, Sample B, by the Royal Aircraft Establishment, Farnborough. Structure, fibre and resin types are given in Table 1.

Table 1

CFC test material data

Sample	Fibre	Resin	Lay-up
B	-	Phenolic*	16 plies; 0°, 90°
C	SUPER A	Code 69	10 layers of cloth; 0°, 90°
D	SUPER A	BSL914C	16 plies; 0°_8, $\pm45^\circ_8$
E	SUPER A	"	16 plies; 0°_8, $\pm45^\circ_8$
F	SUPER A	"	8 plies; ±45°
G	SUPER A	"	16 plies; 0°_8, $\pm45^\circ_8$
H	SUPER A	"	Unidirectional; 0°, 16 plies
I	SUPER A	"	40 plies; 0°, 90°, ±45°
L	SUPER A	"	16 plies; 0°_8, ±45°
P5	HM (High Modulus)	Code 69	90°, +45°, 0°, -45°, -45°, 0°, +45°, 90° 8 layers repeated five times

* Determined by analysis to be a phenolic type

The CFC sheets were generally supplied in rectangular form. Arbitrary orthogonal directions x and y were noted parallel to the sheet edges and samples, 25mm x 10 mm and 25mm x 5 mm, were cut using a hacksaw and marked 'x' and 'y'. Additional samples were cut at an angle of 45° to 'x' and 'y'. All edges were smoothed using a medium-fine grade of glass-paper and finished with fine grade carborundum paper. The 25 mm x 10 mm or 25 mm x 5 mm faces were not abraded as good adhesion and electrical contact were not required on these surfaces.

Samples were then wrapped in two layers of PVC adhesive tape of width 20 mm so that a 2.5 mm length at each end of the samples was exposed. The samples were then immersed in a sensitiser solution for 10 to 15 minutes, washed thoroughly and immersed in an electroless plating solution until an adequate deposition of copper was obtained. 30 to 50 minutes were required for this to occur. Details of this process were supplied by Plessey Research (Caswell) Ltd and their full instructions are to be found in the Appendix to this chapter.

The samples were washed, dried and soft soldered into the jig of Fig.2, or the inductor end pieces of Fig.3 were soldered as required for tests at higher frequencies. As indicated in Fig.4, less plating occurred on the main faces (these retained their epoxy resin surfaces and unwanted plating could be removed, if required, using a screwdriver tip).

Entry of current into the sample was largely at the 10 mm x thickness or 5 mm x thickness plated areas at the sample ends.

Direct electroplating using acidified copper sulphate solution and a suitable plating current resulted in a mechanical bond which appeared somewhat superior to that obtained with the electroless plate but d.c. tests revealed that the electrical bond was significantly inferior.

An electroplate on top of the electroless plate may be advantageous, in that a limited number of tests seemed to indicate a reduced sensitivity to soldering where excessive temperature or duration of melt can increase contact resistance. This occurs, presumably, when thermal expansion breaks a number of the copper-fibre bonds.

In connection with the short transmission line tests referred to in Section 2.2, a sample of unidirectional CFC material, Hy, 200 mm x 12 mm x 2.11 mm was connected as shown in Fig.5. The sample was cut with fibres parallel to main current flow and electroless copper plated at each end, thus allowing it to be soft-soldered into the line.

4 RESULTS

4.1 Measurements on small samples using Q-meter

Graphs of resistivity for samples cut in the 'x' and 'y' directions and at 45° are shown in Figs.6-25. To facilitate comparison, all (except

for Sample H) are presented on the same scales. Results for Sample H in directions not parallel to the unidirectional fibre lay indicate much greater resistivity and are necessarily plotted to a different scale. Also to aid comparison, results for each sample, cut in the three directions, are shown on one page.

Resistivities are generally lower for the narrower 25 mm x 5 mm samples. This is consistent with the existence of a skin effect for current flow, since in the narrower sample the loss in effective cross-sectional area will be proportionately less than in the wider samples as current retreats to surfaces and edges with rise in frequency.

This change in distribution of current over the cross-section (skin-effect) occurs because those parts of the cross-section which are circled by the largest number of magnetic flux lines have a greater inductance than other parts and hence a greater reactance. Those parts having the greatest reactance will carry the least current. With a flat strip, as used here, the current density is greatest at the edges, reduced at the flat surfaces and least in the centre. Hence skin depth of current flow controls the resistance for alternating currents. From Maxwellian theory it can be shown (Refs.7 and 8) that skin depth is proportional to $f^{-\frac{1}{2}}$ and high frequency resistance is proportional to $f^{\frac{1}{2}}$ in a conductor of circular cross-section. Intuitively, it is apparent that resistance must increase by a power of f which is less than unity because as current moves towards the outer surface of a conductor with rise in frequency, the effective area of an elementary annulus of cross-section is increasing with distance from the centre of the conductor.

Graphs are included which show resistivity plotted against $(\text{frequency})^{\frac{1}{2}}$ for all the test samples. Linear relationships exist over much of the frequency range confirming the presence of skin effect. Most of the graphs show two $f^{\frac{1}{2}}$ proportional regions of differing slope, the change-over point often occurring at about 200 MHz. This effect is less evident with Samples D, H and I (y).

In the case of the unidirectional sample H(y) (Fig.18) where the fibres are laying in the main direction of current flow, the d.c. resistivity is shown as 2.1×10^{-5} Ωm. The sample contains Super A fibres of resistivity ~1.3×10^{-5} Ωm. On this basis the fibre content of the sample is

approximately 62%. It has been indicated elsewhere (Refs.9 and 10) that volume fractions for CFC materials vary from about 0.60 to 0.65.

Table 2 shows the range of resistivities obtained at a number of frequencies, which are characteristic of panels where good contact is maintained by copper plating at the current entry and exit surfaces.

Table 2

Ranges of resistivities for CFC materials

Frequency MHz	Ranges of resistivity - all samples (except unidirectional) 10^{-5} Ωm	Resistivity for unidirectional samples 10^{-5} Ωm: Parallel to lay	Resistivity for unidirectional samples 10^{-5} Ωm: Perpendicular to lay
1	3 to 15	2	1100
10	5 to 15	6	1100
50	12 to 35	12	1300
100	17 to 60	16	-*
300	32 to 150	30	-*

*Measurement not feasible

As an additional check a 22 mm length of Eureka resistance wire of diameter 0.13 mm was measured for resistance at d.c., and at 50 MHz and 250 MHz in the test jigs used for evaluating the characteristics of the CFC samples. Table 3 shows the results obtained together with the theoretical values applying to a wire of these dimensions and type.

Agreement is reasonable, but as there is a large transition in conductor dimensions where the thin wire joins the 10 mm width of inductor strip used at 250 MHz, further tests were made with a carbon rod with electroless copper plated ends where the dimensions of the rod (25 mm x 8 mm diameter) are comparable with those of the CFC samples.

Table 3

Variation of wire resistance

Frequency MHz	Calculated resistance Ω	Measured resistance Ω
d.c.	0.82	0.82
50	0.87	0.90
250	1.40	1.67

Table 4

Variation in resistance of carbon rod sample

Frequency MHz	Calculated resistance (based on measured d.c. value) Ω	Measured resistance Ω
d.c.	-	0.031
1	0.031	0.031
50	0.12	0.14
250	0.26	0.33

Table 4 shows that the carbon rod sample is behaving in a reasonable manner in the test jig used for the evaluation of the CFC samples. The measured resistance is 27% higher than calculated at 250 MHz but in view of the difficulties of measurement and connection of the sample this error is not regarded as excessive and the results shown in Tables 3 and 4 are regarded as confirming the validity of the data gathered on CFC materials.

Q-meter accuracy is claimed as ±5% up to 10 MHz, rising to ±12% at 200 MHz and ±20% at 300 MHz. An assessment of overall accuracy in the determination of the resistivity of the CFC samples is difficult, but limits of ±10% up to 10 MHz, ±20% from 10 MHz to 50 MHz and ±30% from 50 MHz to 300 MHz are probably realistic. Repeatability of measurements has proved to be about ± 5%.

4.2 Measurements using unidirectional samples (type H(y)) in a transmission line

As noted in Section 3 and shown in Fig.5, a sample of unidirectional CFC material H(y) was connected as part of a short-circuited transmission line.

This sample was tested using the Hewlett-Packard vector impedance meter type 4815A adopting the precautions noted in Section 2.2 above.

Figure 26 shows the results obtained and the resistance of the sample was found to increase markedly with frequency. The sample was then examined using the Q-meter and these results are also shown in Fig.26. A sample of this size is not well suited to the Q-meter technique, but the results obtained are comparable with those using the vector impedance meter. The resistivity values obtained by Q-meter at frequencies above 30 MHz are probably less accurate, as the jig method, Fig.2, is inappropriate, and an initial Q value Q_1 must be obtained by using a 'dummy' shorted transmission line in which a brass strip replaces the CFC sample.

Figure 27 shows the vector impedance meter results again but now these are compared with those found using the 25 mm x 5 mm sample of H(y) material previously shown in Fig.18. The length to width ratio for the transmission line sample is 16.7 compared with 5 for this Q-meter sample. Results differ by a maximum of 15% at frequencies up to 50 MHz. For such low resistance samples (the 200 mm strip has a d.c. resistance of 0.18 Ω) the accuracy of the vector impedance meter is much reduced above about 50 MHz, and the use of the Q-meter (with smaller samples) is preferred.

In Fig.28 the resistivity of the transmission line sample as measured by the vector impedance meter is plotted against a scale proportional to $f^{\frac{1}{2}}$.

It will be seen that a linear relationship occurs suggesting the existence of a normal skin effect for current flow.

The measurements show that results obtainable using a Q-meter are in good agreement with those made using the vector impedance meter and both methods demonstrate the presence of skin effect.

5 THE CALCULATION OF RF RESISTANCE OF CFC SAMPLES

A method for the calculation of the resistance of samples over a range of frequencies would be of considerable value and the measurements made on the ten types of material listed in Table 1 could provide ample validation for such procedures.

Belevitch (Ref.11) considers lateral skin effect in a flat conductor having a thickness t and a width or lateral dimension w. At frequencies where $t \ll \delta$ (δ = skin depth) the current density is still uniform along the thickness coordinate and the only problem is the lateral distribution of the linear current density along the width coordinate. Belevitch deals only with the lateral distribution problem as the depth penetration occurring at much higher frequencies is well understood. His analytical treatment for conductors of elliptical cross-section is complete but an analytical approach is not suitable for conductors with sharp edges (e.g. rectangular cross-section). Numerical treatments are required and only partial solutions could be obtained. Figure 29 gives a qualitative indication of R_{ac}/R_{dc} for such a conductor. The section of the curve AB represents the lateral phase and CD the depth penetration phase. The total response depends in part on an 'asymptotic mode' BCE, '<u>the law of which remains to be discovered</u>'.

In view of these limitations in the theoretical description of the high frequency behaviour of homogeneous isotropic materials of rectangular cross-section it appears that no rigorous treatment for the apparently more complex case of CFC can be envisaged at the present time.

A simpler approach to this problem has been tried at ERA and the obvious sample for an initial consideration is H(y), the unidirectional material, with main current flow in the 0° direction (i.e. in the direction of the fibre lay).

Haefner (Ref.12), in 1937, described a method based on experimental evidence for calculating the alternating current resistance of conductors of rectangular cross-section (see also Terman (Ref.13)). Haefner's corroborative measurements were made at frequencies up to 8 kHz but his examination of data from other sources suggested that good agreement between theory and measurement would be maintained at much higher frequencies. Figure 30 shows how the ratio R_{ac}/R_{dc} is related to a parameter p for various ratios of width to thickness of the cross-section of the sample.

If Haefner's treatment is applied to sample H(y), the unidirectional material, and the d.c. resistivity used as the basis for calculating resistivity at high frequencies, it is found that the calculated values, although of the same form, are substantially lower than those obtained by measurement.

Clearly, a more rigorous treatment is required and proximity effects (Refs.14 and 15) in bundles of fibres have been considered as an additional factor. No convincing theory has been evolved, however, which provides better agreement with measurements. Experimental results for the 10 CFC materials have been included in full in Figs.6-25 of this chapter to assist those who wish to further examine this subject.

6 CONCLUSIONS

Resistivity has been obtained for 10 types of CFC material where measurements have been made in two orthogonal directions and at 45° to these. In the case of unidirectional CFC, the resistivity of the composite material at d.c. and low frequencies, and where main current flow is in the direction of the fibre lay, is consistent with the expected fibre volume fraction of 0.6 to 0.7.

Skin effect develops in all samples in a manner similar to that for a homogeneous isotropic material when connections to the test samples are made in the manner described. The effect can be measured by Q-meter or vector impedance meter techniques. The Q-meter is usable at frequencies up to 300 MHz, whereas the vector impedance meter is limited to 108 MHz and is not well suited to the low resistance of CFC samples.

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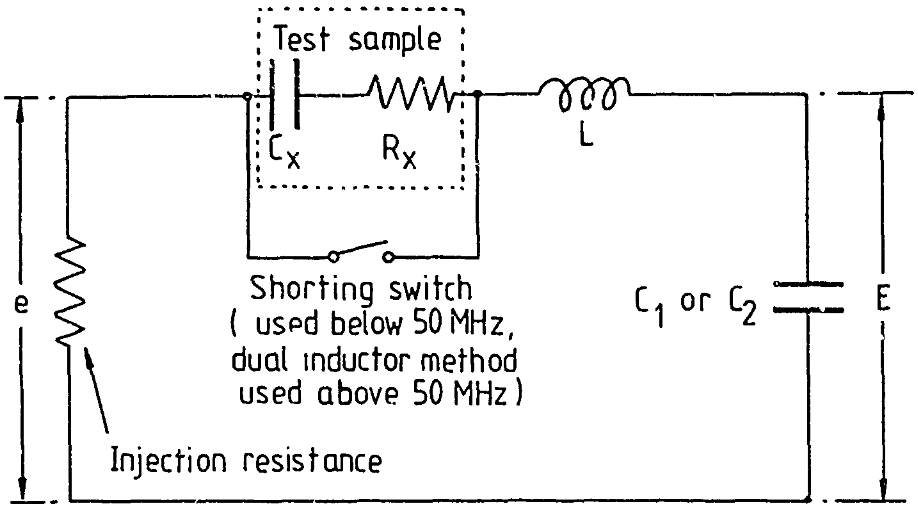


$$Q = \frac{E}{e}$$

$$R_x = \frac{1}{\omega}\left[\frac{1}{C_2Q_2} - \frac{1}{C_1Q_1}\right]$$

$$C_x = \frac{C_1C_2}{C_2-C_1}$$

C_1 & Q_1 obtained with sample shorted

C_2 & Q_2 obtained with sample in circuit

Figure 1 Q-meter test circuit

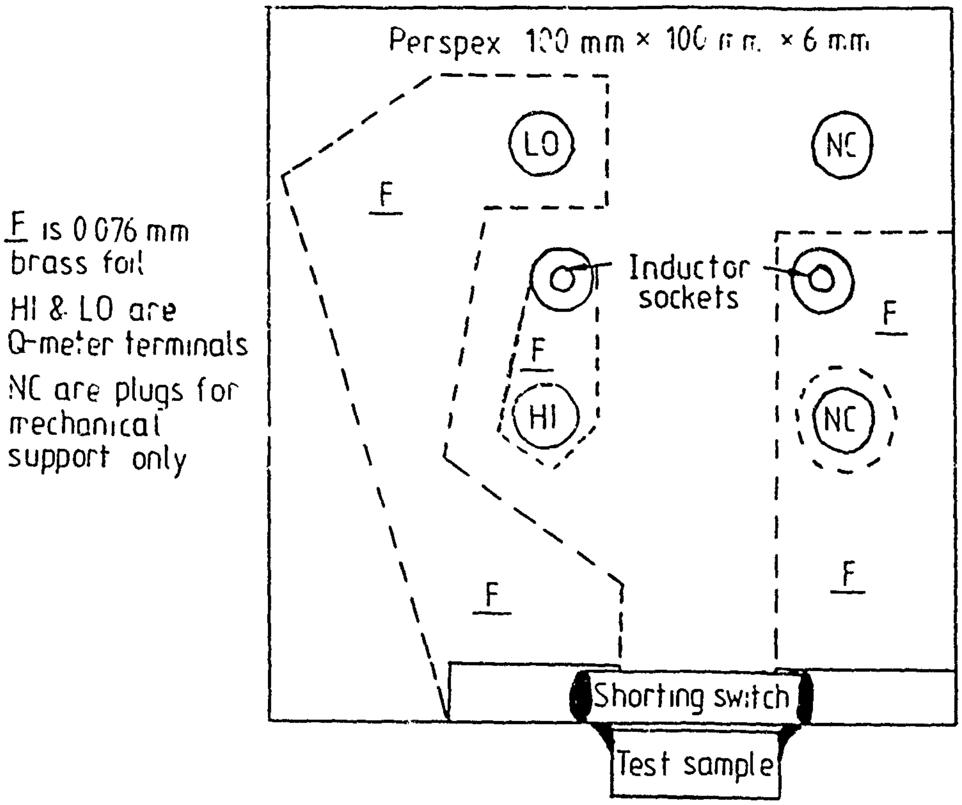


Figure 2 Test jig, 1-50 MHz

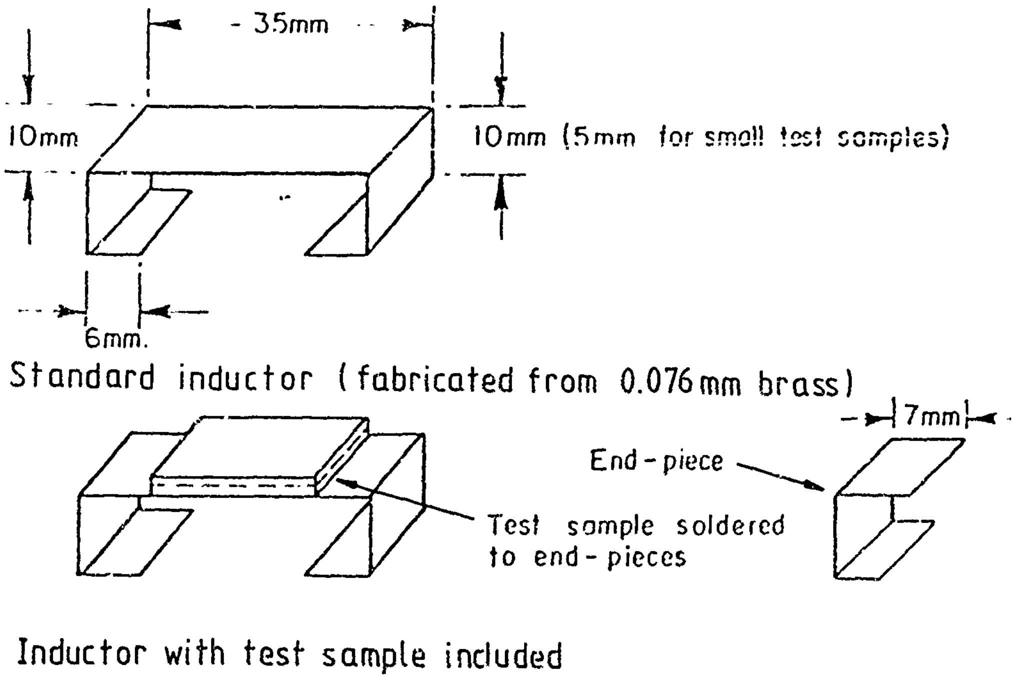


Figure 3 Test samples for 100-300 MHz

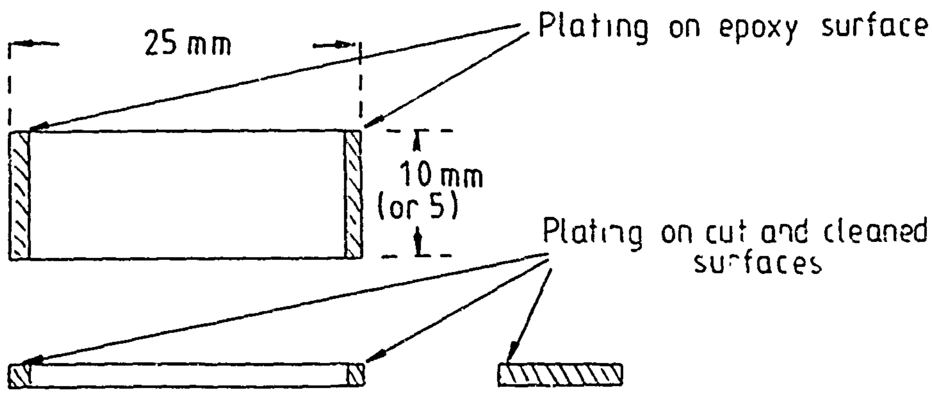


Figure 4 Plated sample

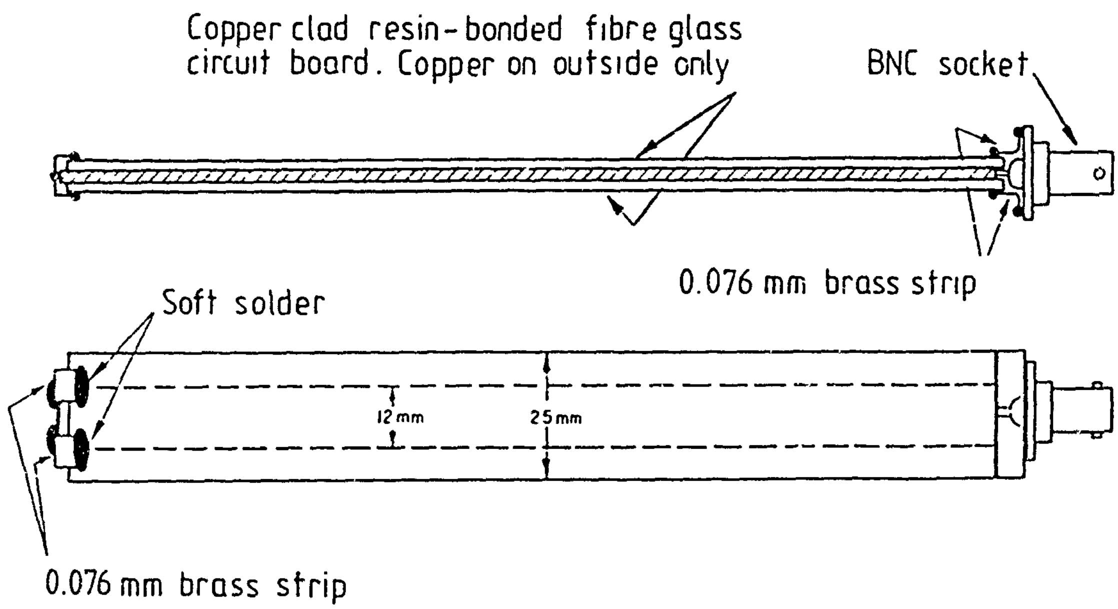


Figure 5 Transmission line sample of unidirectional material H(y), length 200 mm, thickness 2.11 mm

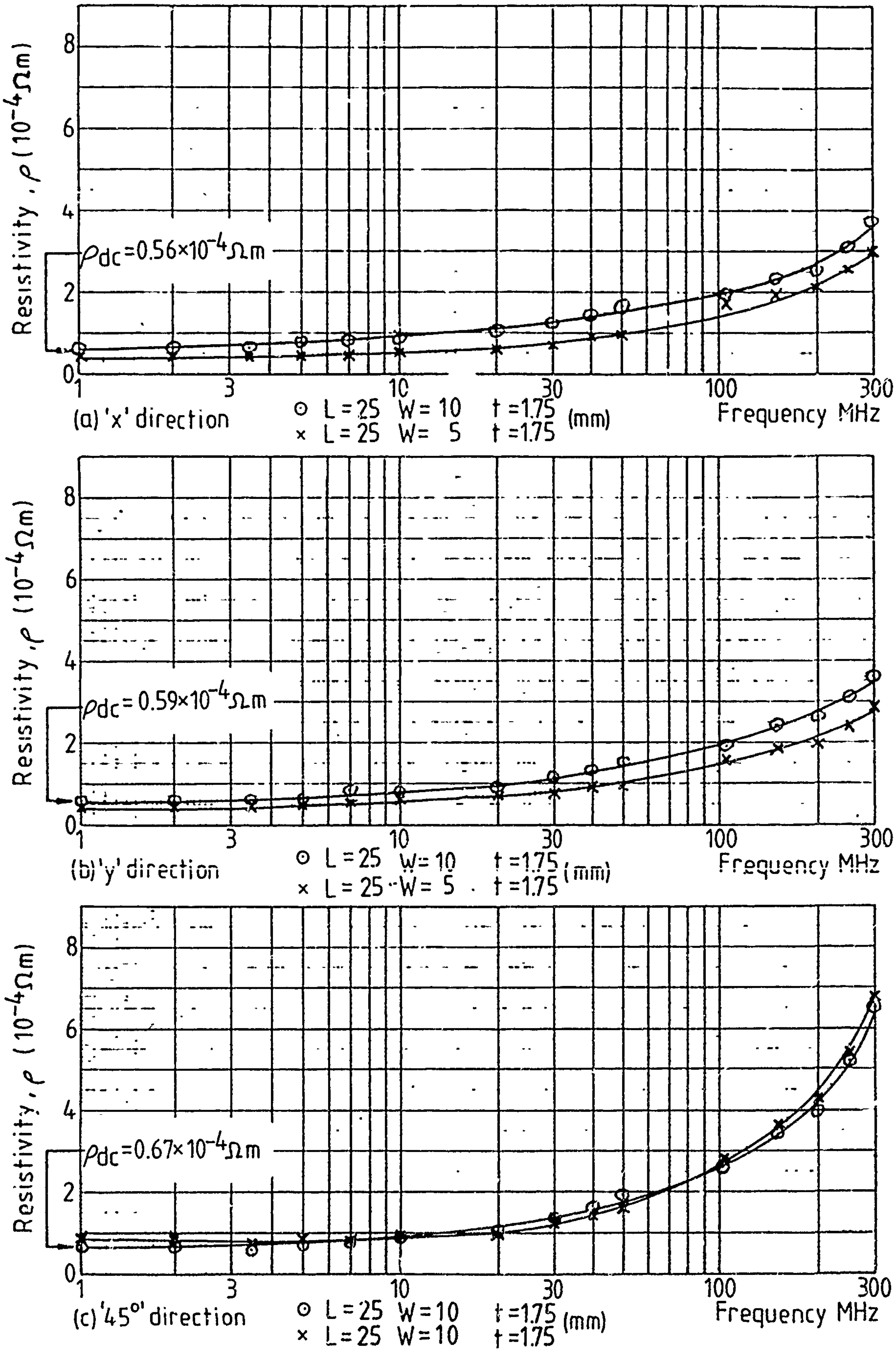
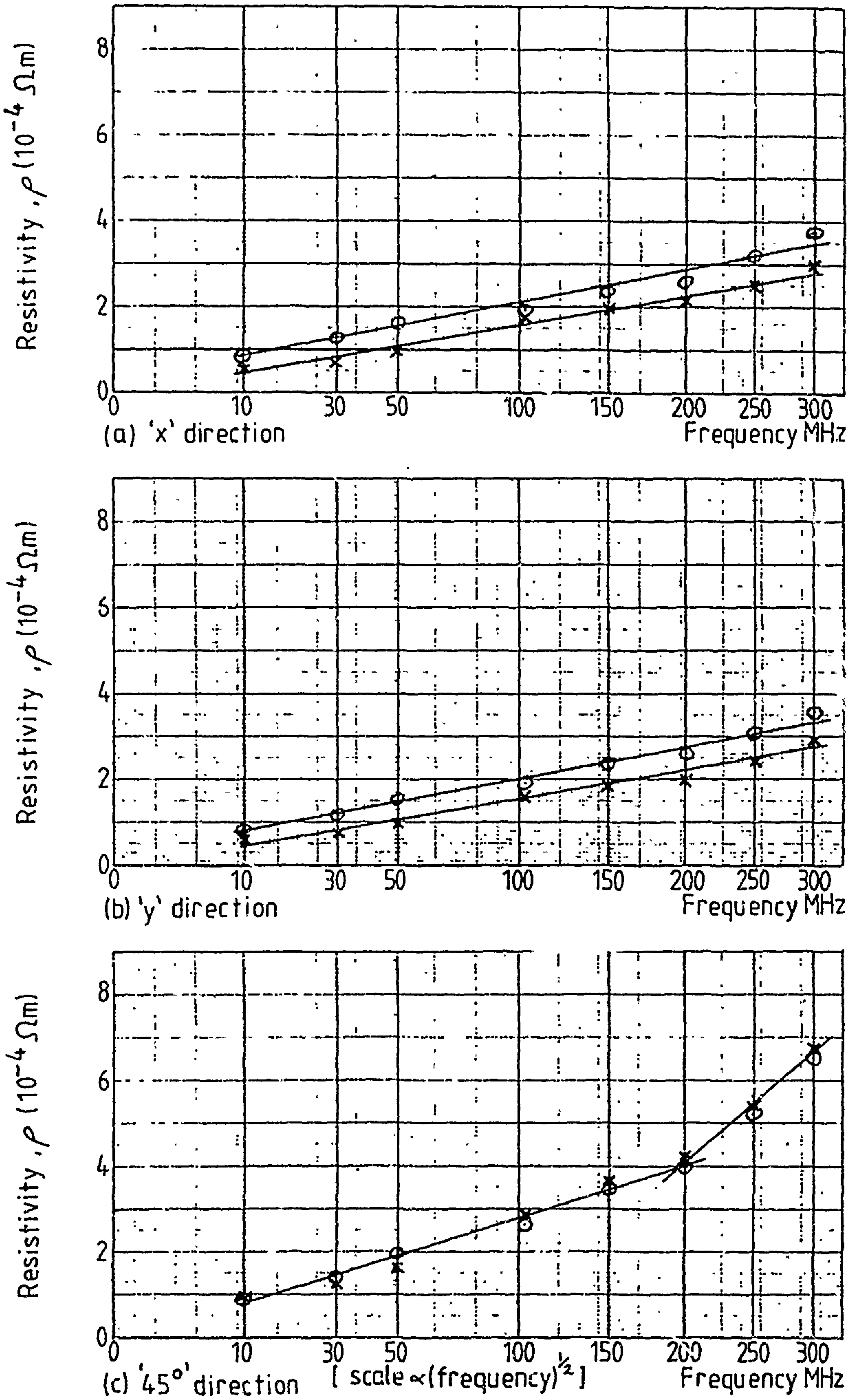


Figure 6 Resistivity-frequency characteristics for sample B



sample details in Fig. 6

Figure 7 Resistivity-frequency characteristics for sample B

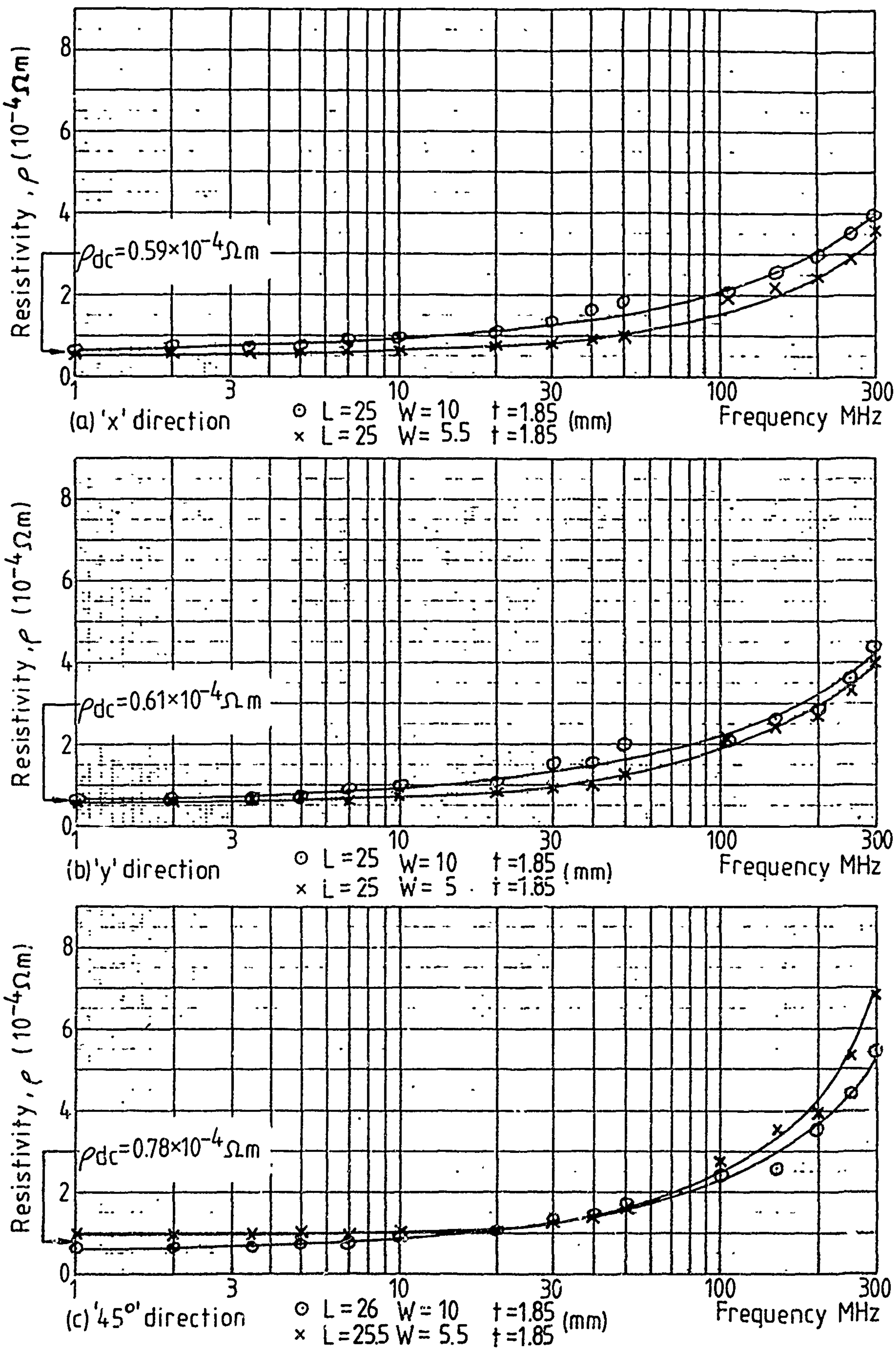
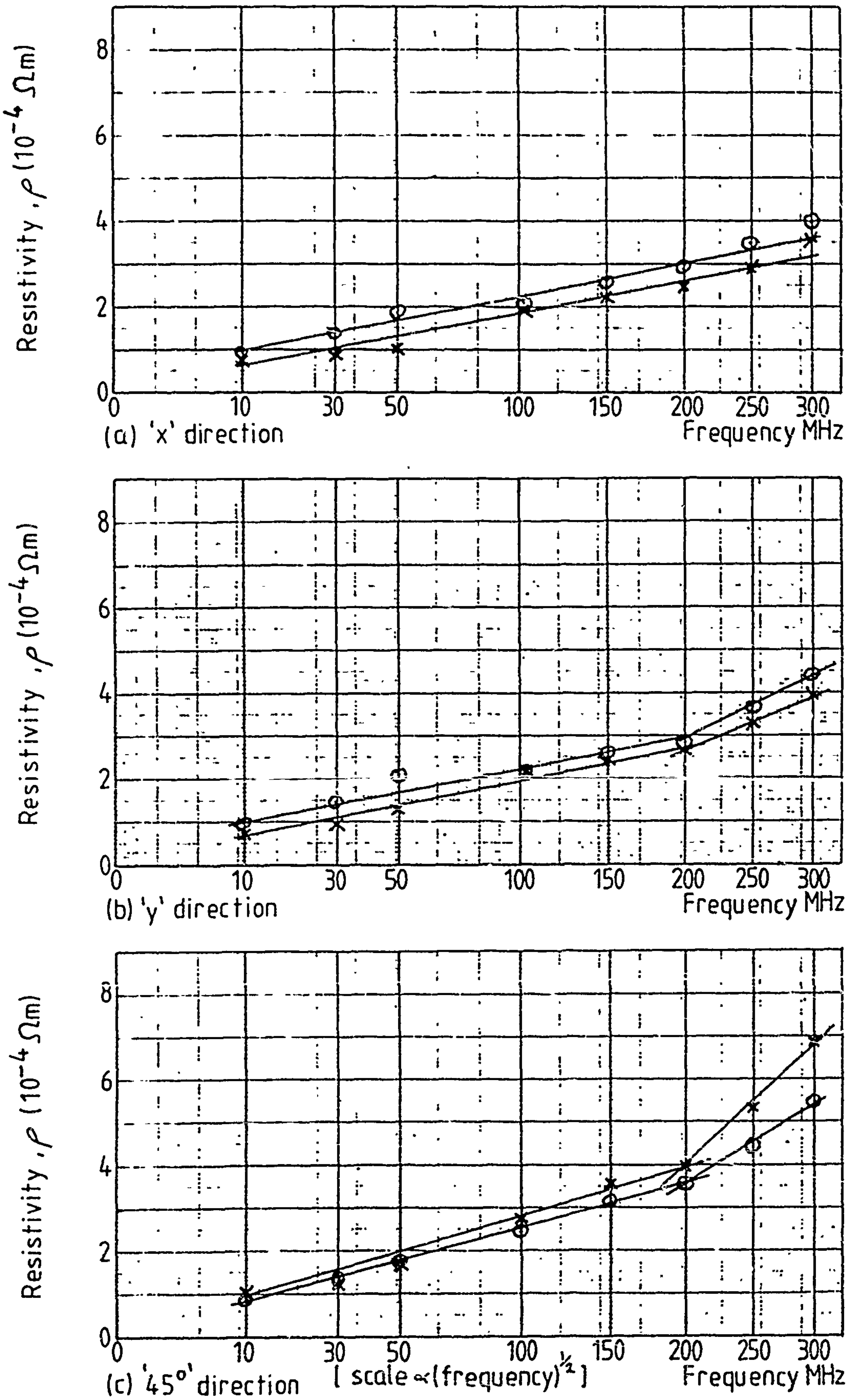


Figure 8 Resistivity-frequency characteristics for sample C



sample details in Fig. 8

Figure 9 Resistivity-frequency characteristics for sample C

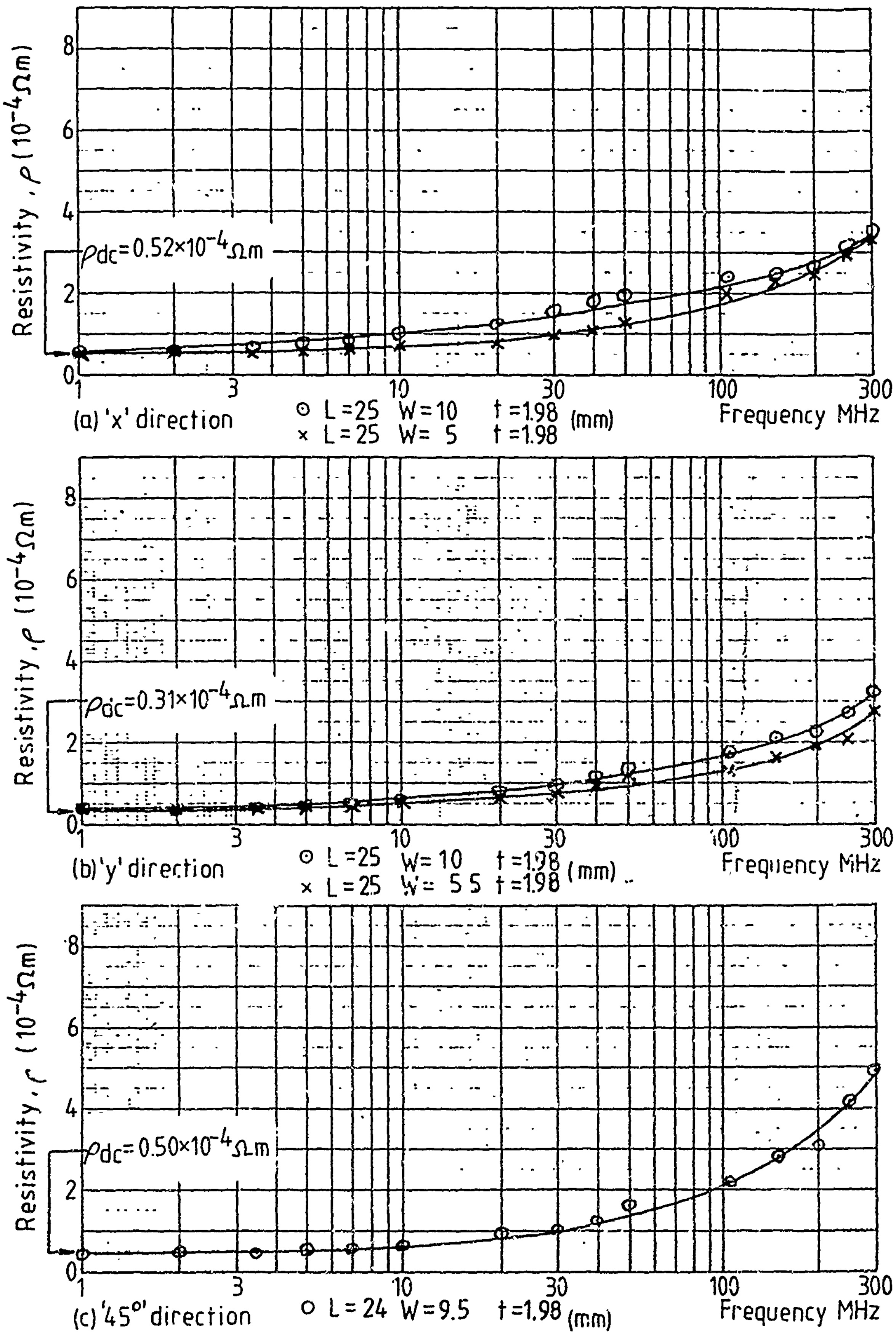
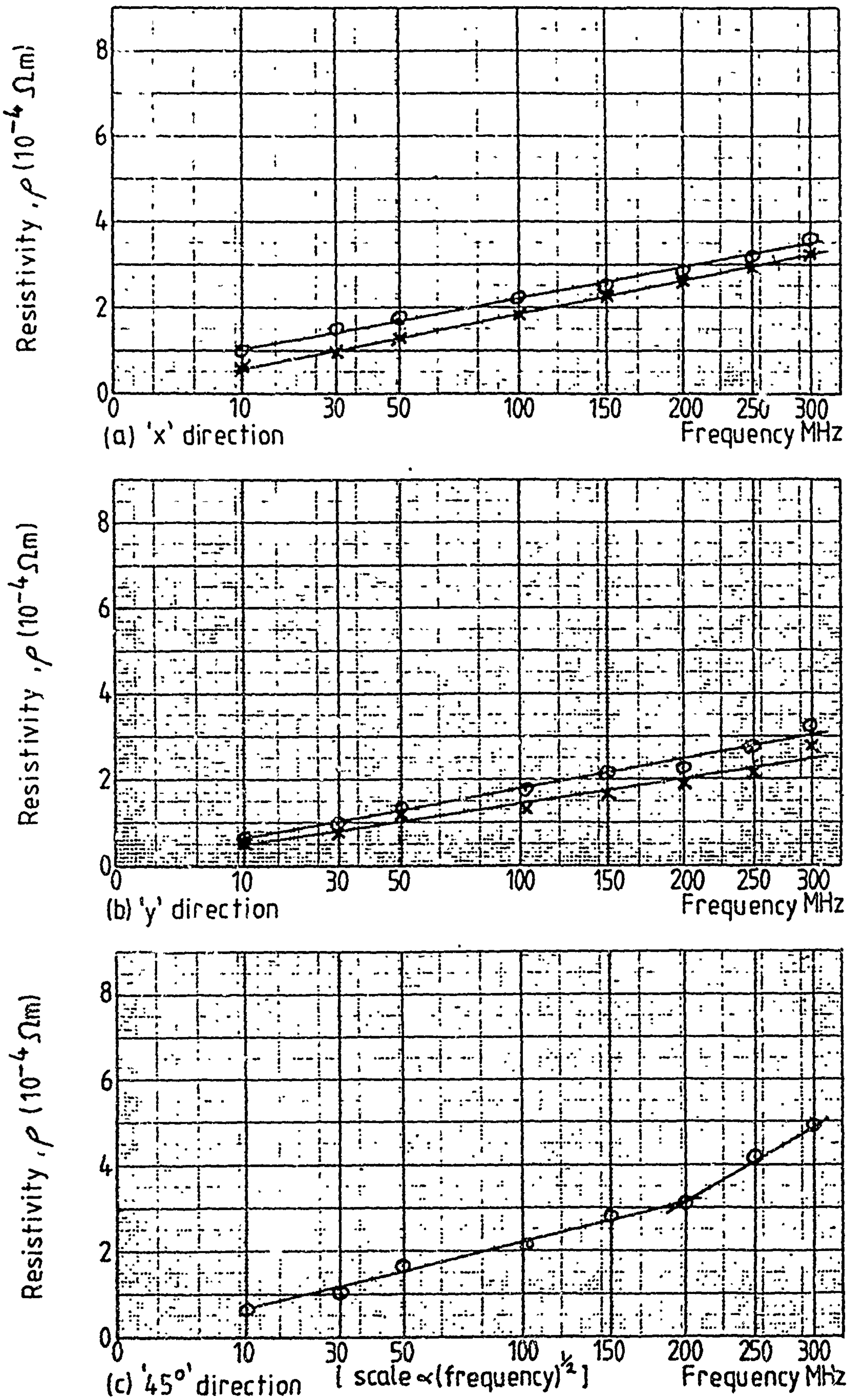


Figure 10 Resistivity-frequency characteristics for sample D



sample details in Fig. 10

Figure 11 Resistivity-frequency characteristics for sample D

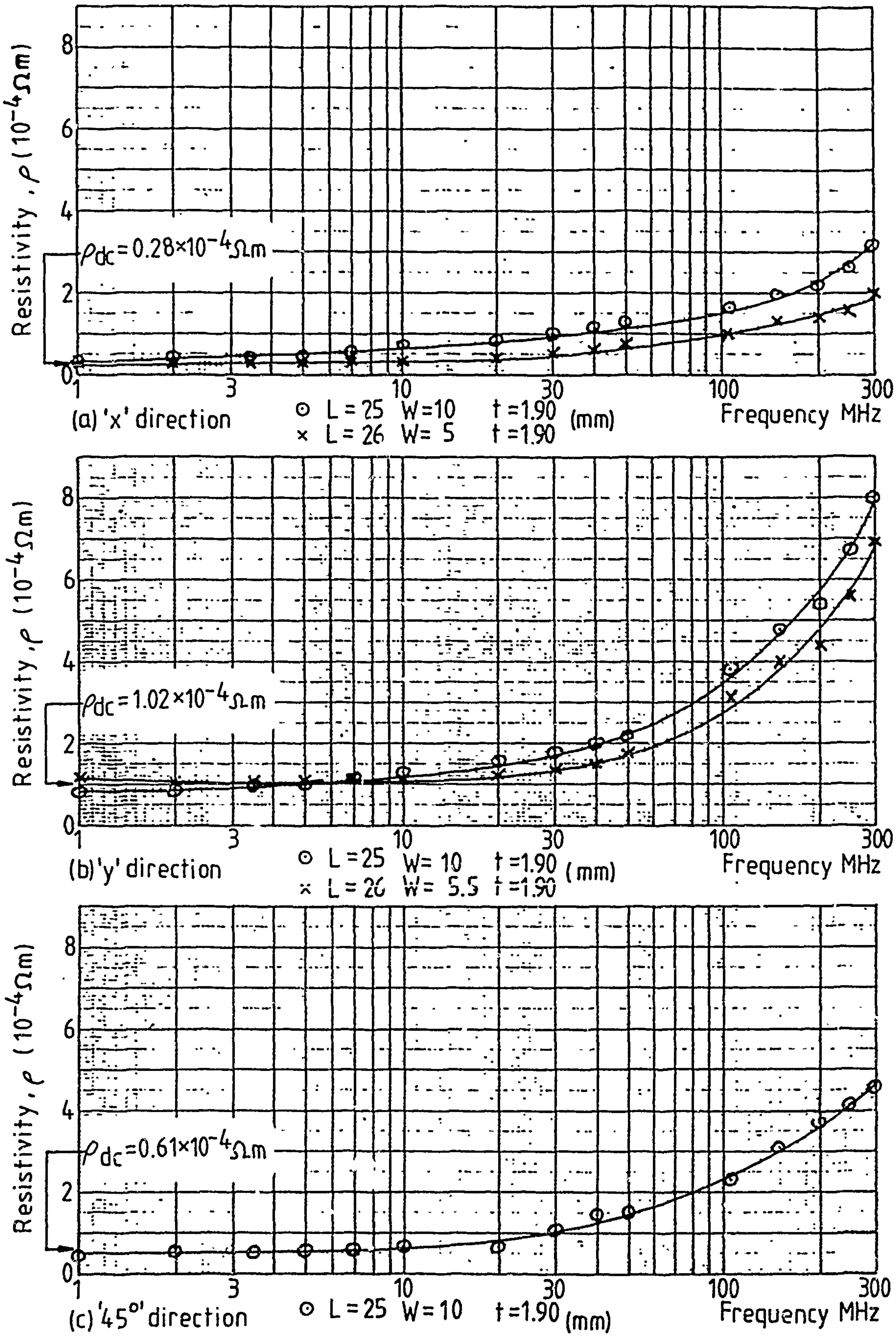
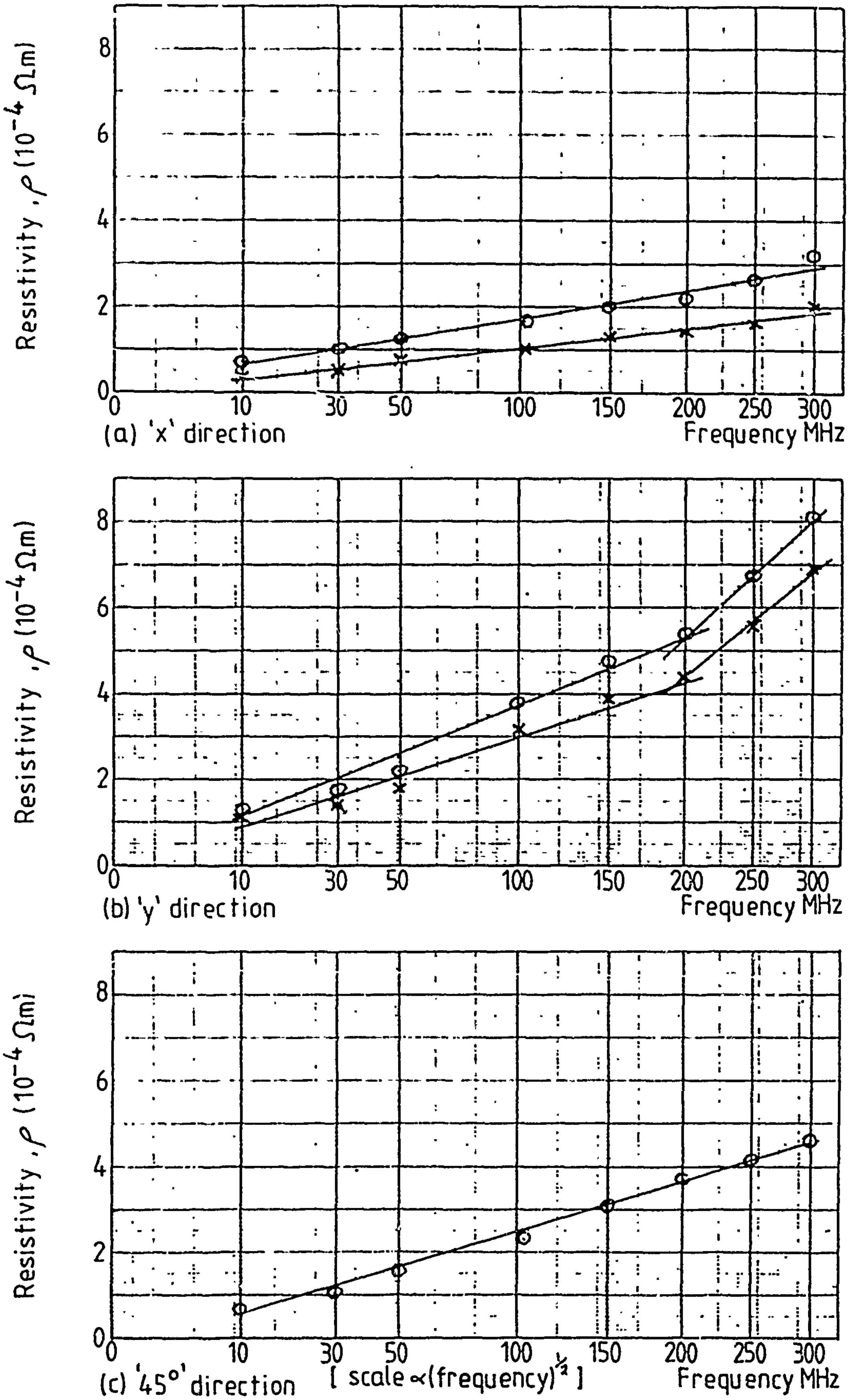


Figure 12 Resistivity-frequency characteristics for sample E



sample details in Fig.12

Figure 13 Resistivity-frequency characteristics for sample E

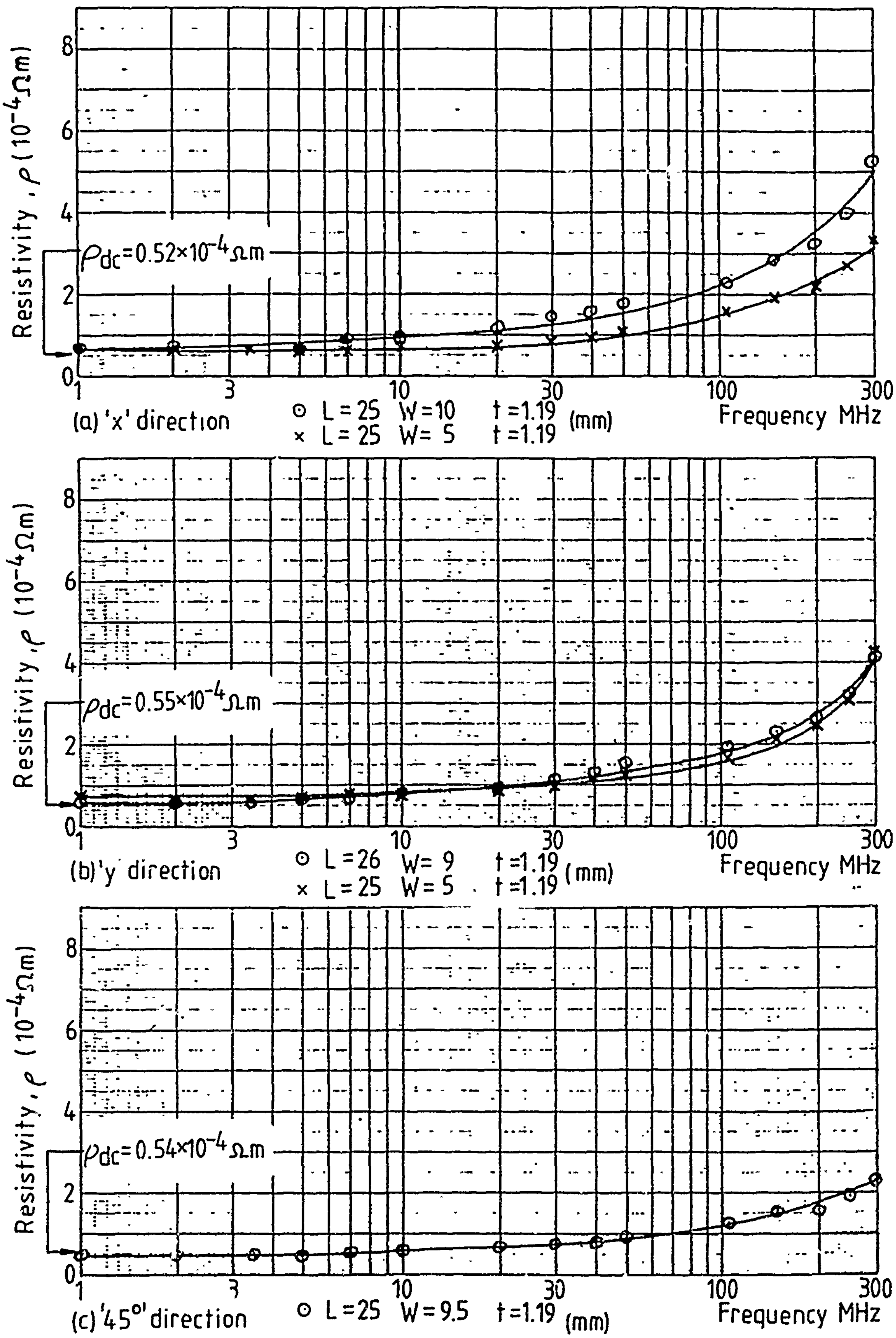
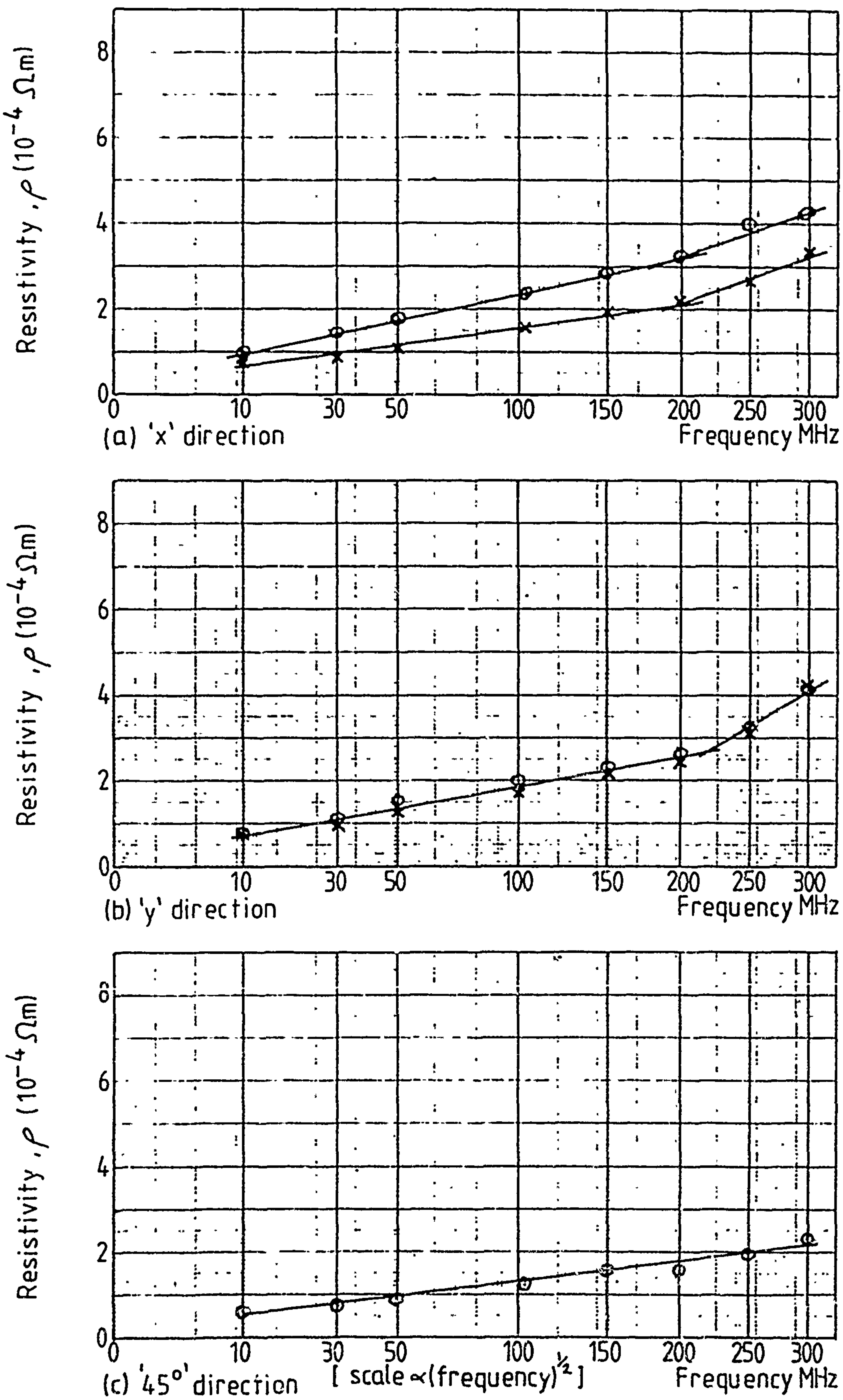
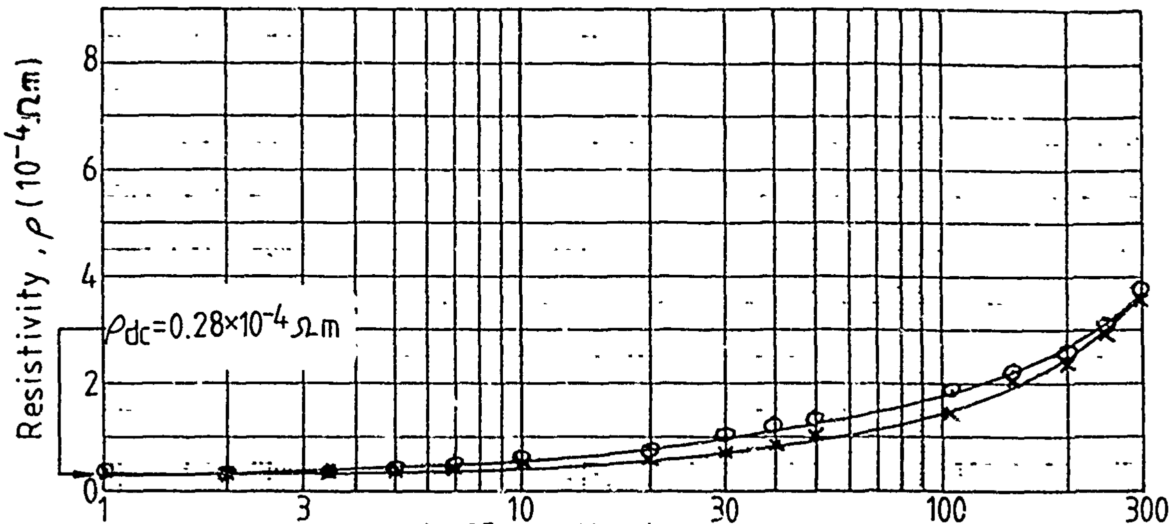


Figure 14 Resistivity-frequency characteristics for sample F

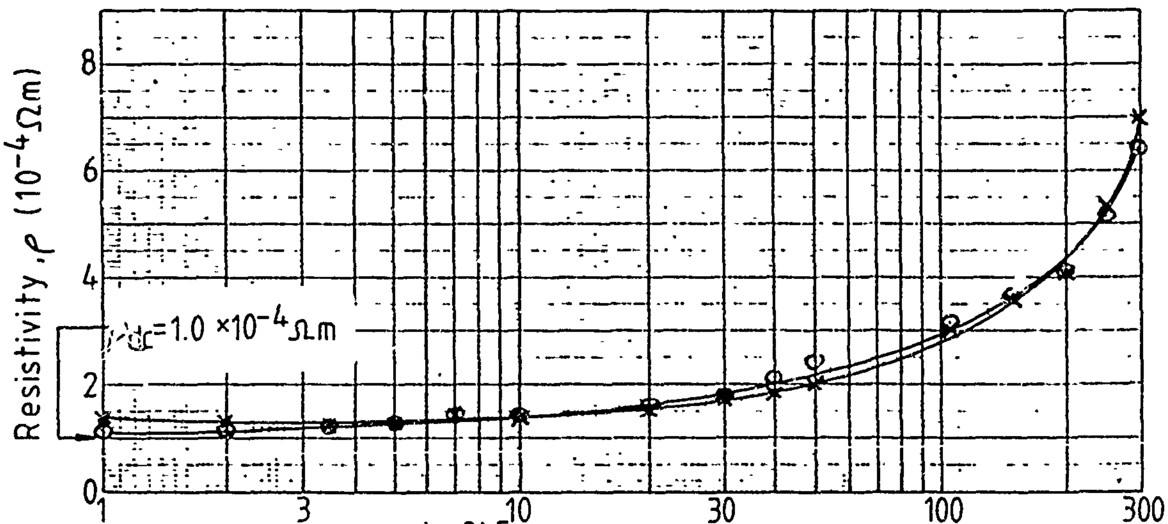


sample details in Fig. 14

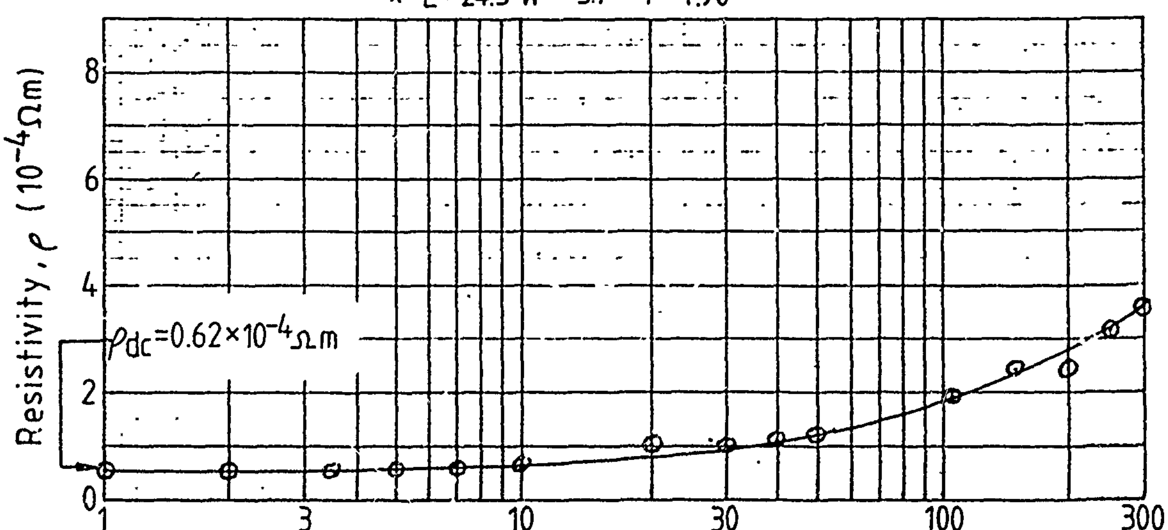
Figure 15 Resistivity-frequency characteristics for sample F



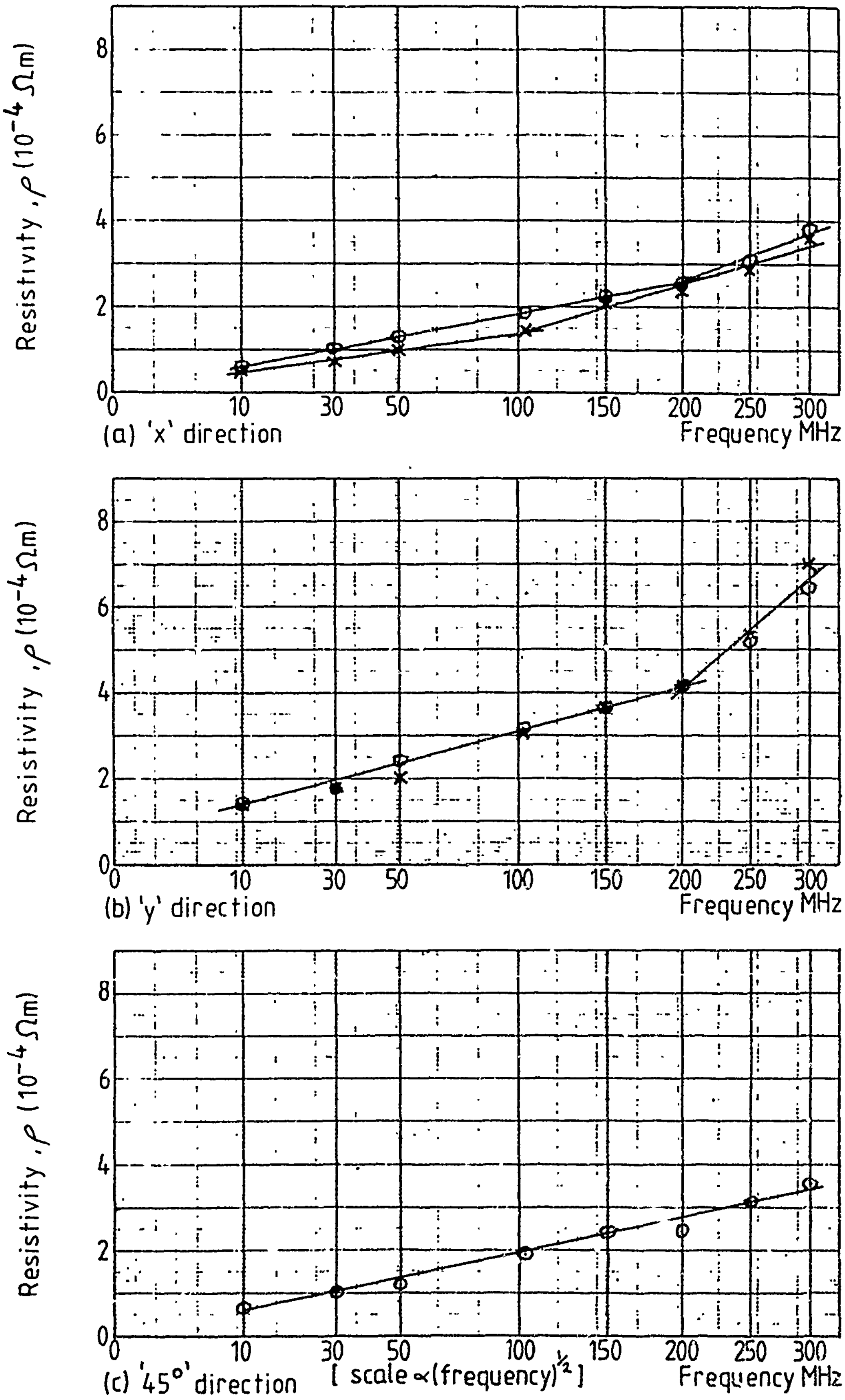
(a) 'x' direction ⊙ L=25 W=10 t=1.90 (mm) Frequency MHz
× L=25 W=5.5 t=1.90



(b) 'y' direction ⊙ L=24.5 W=11 t=1.90 (mm) Frequency MHz
× L=24.5 W=5.7 t=1.90



(c) '45°' direction ⊙ L=24 W=9 t=1.90 (mm) Frequency MHz



sample details in Fig. 16

Figure 17 Resistivity-freque aracteristics for sample G

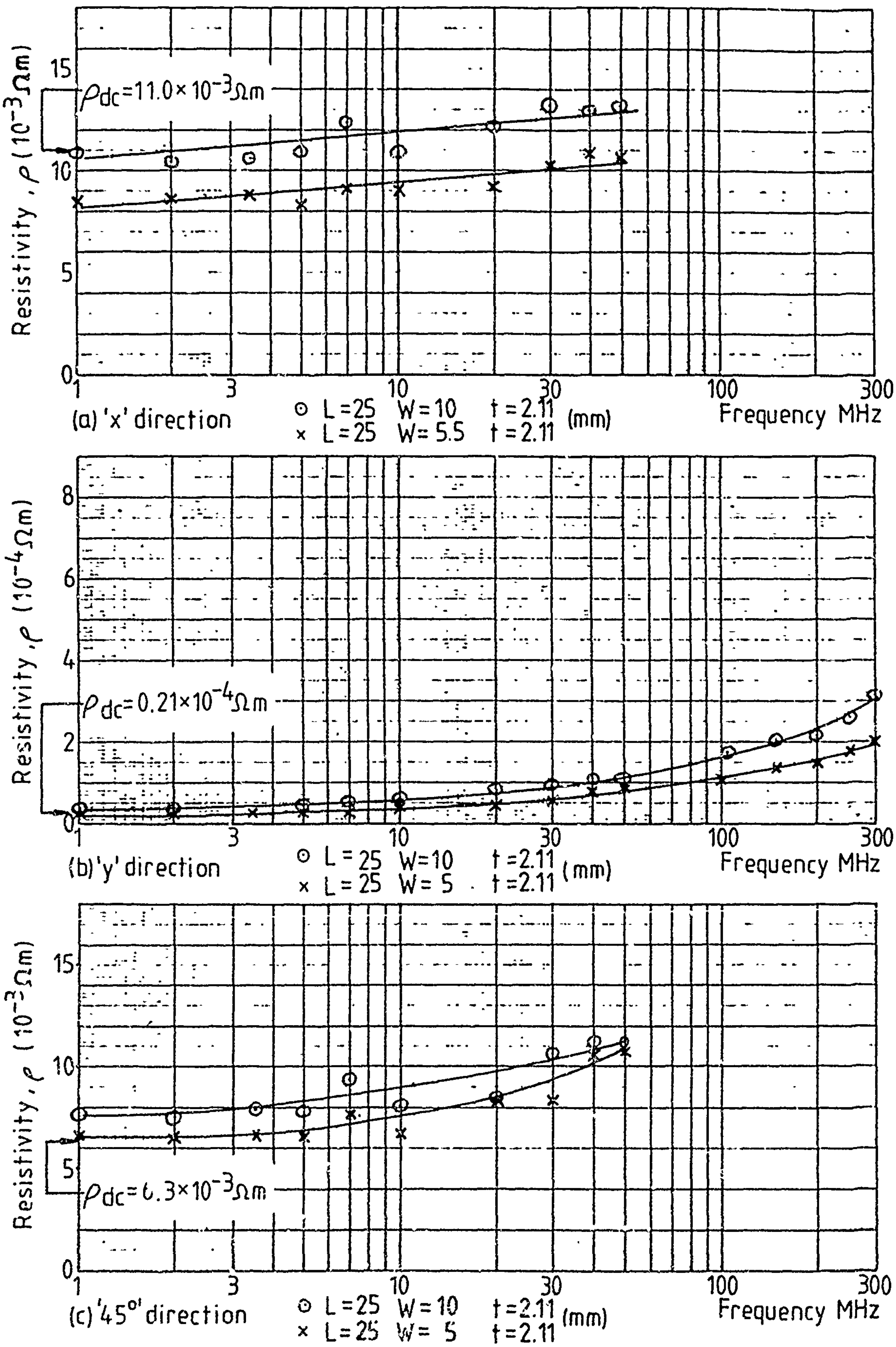
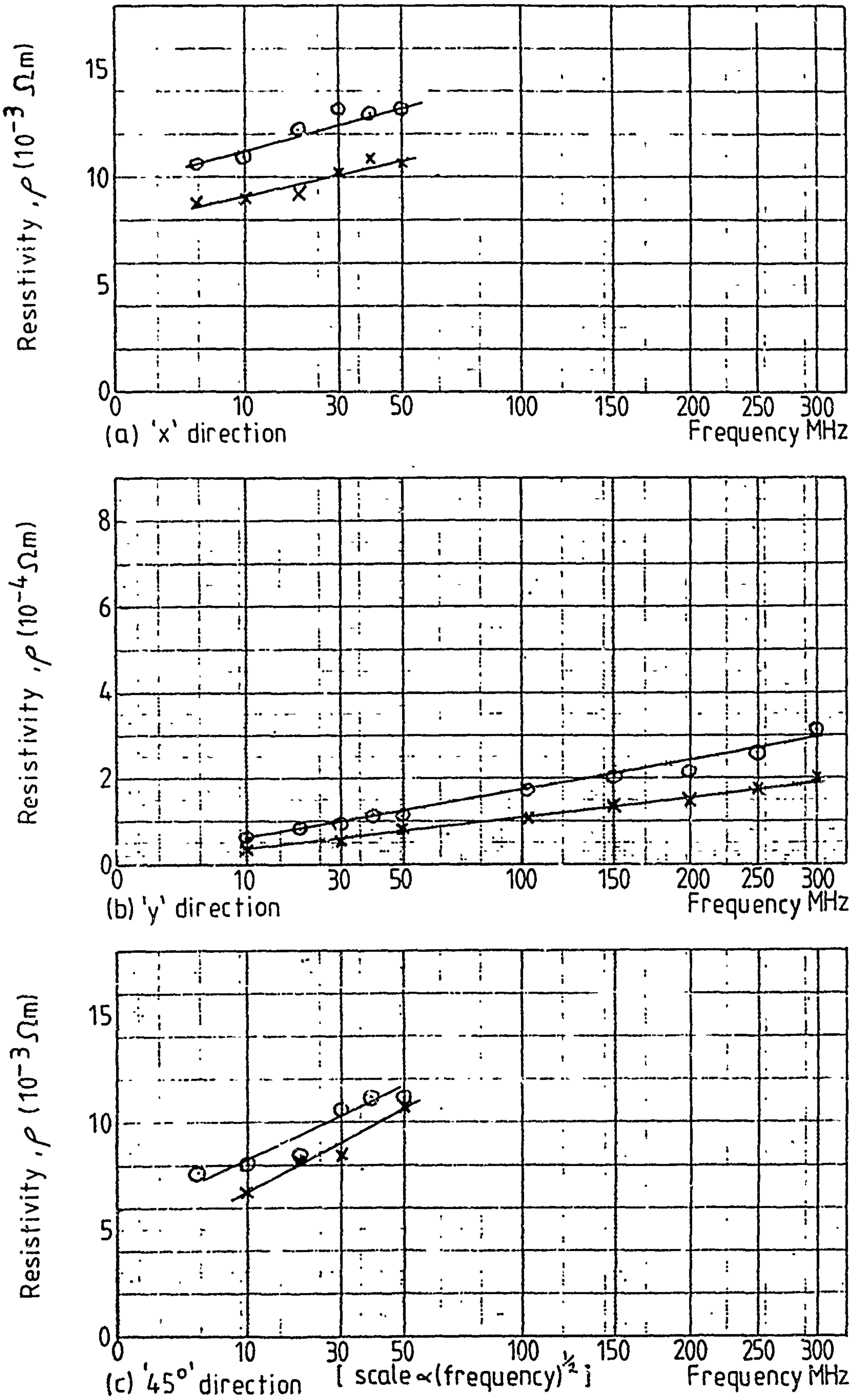


Figure 18 Resistivity-frequency characteristics for sample H



sample details in Fig.18

Figure 19 Resistivity-frequency characteristics for sample H

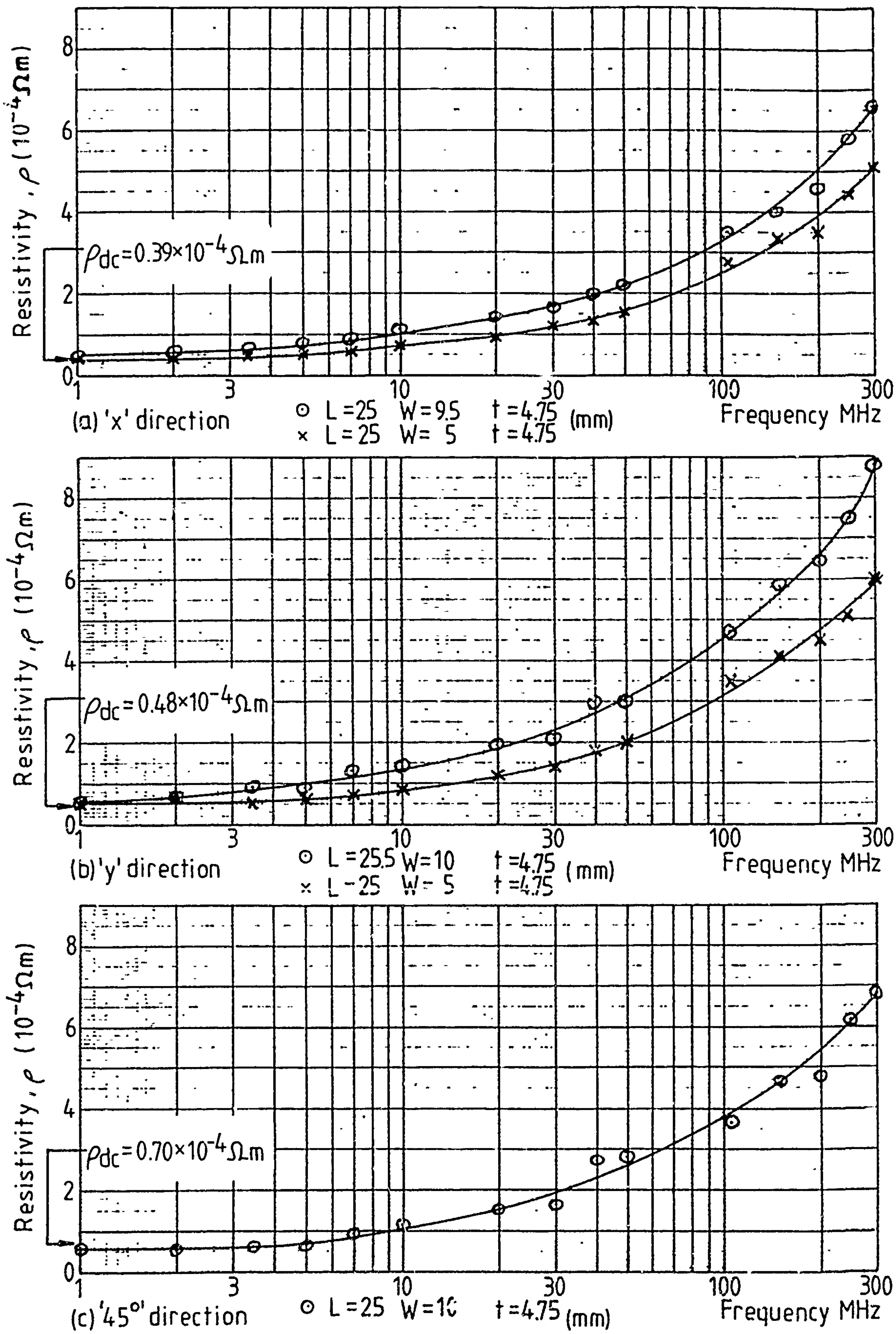
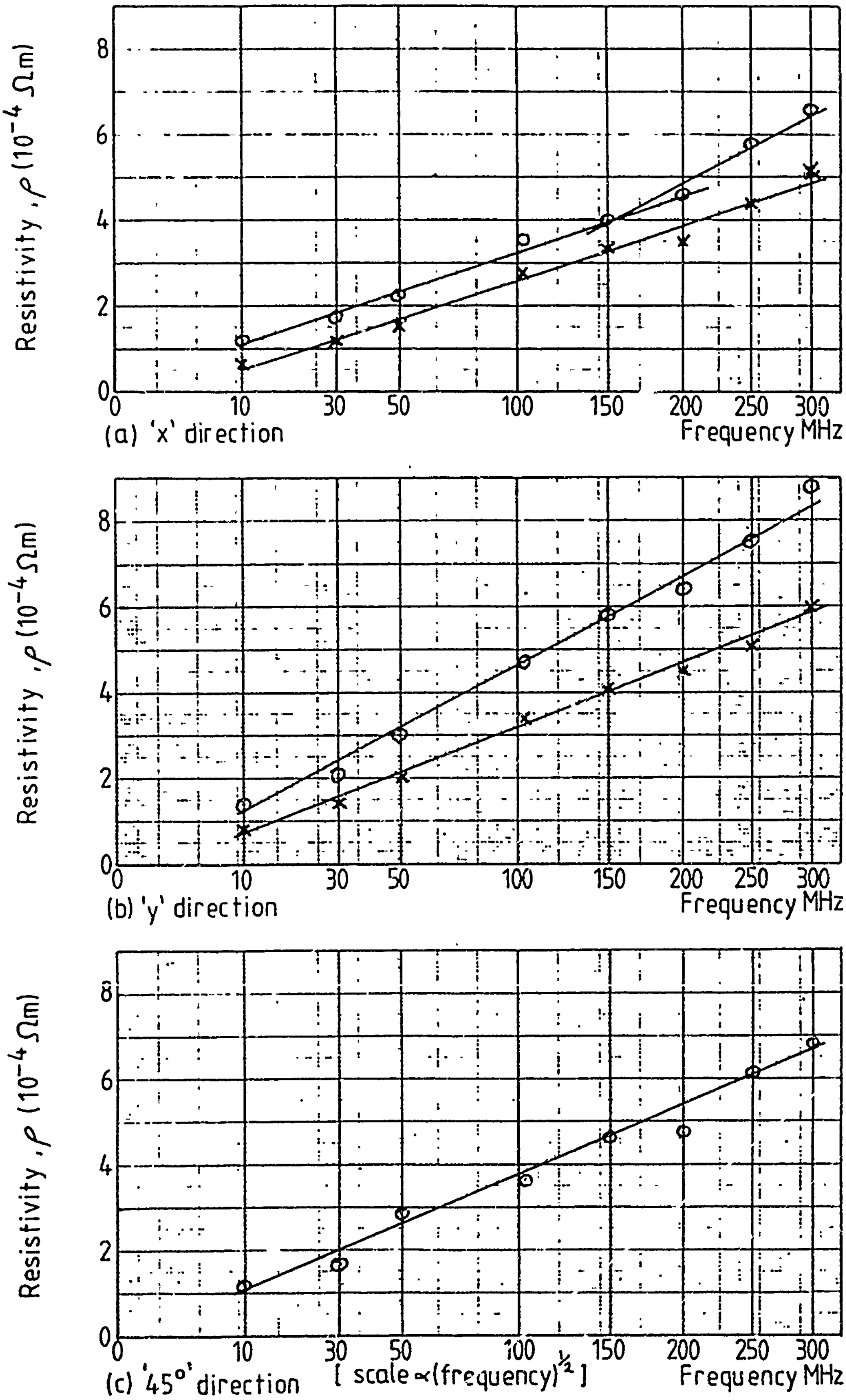


Figure 20 Resistivity-frequency characteristics for sample I



sample details in Fig. 20

Figure 21 Resistivity-frequency characteristics for sample I

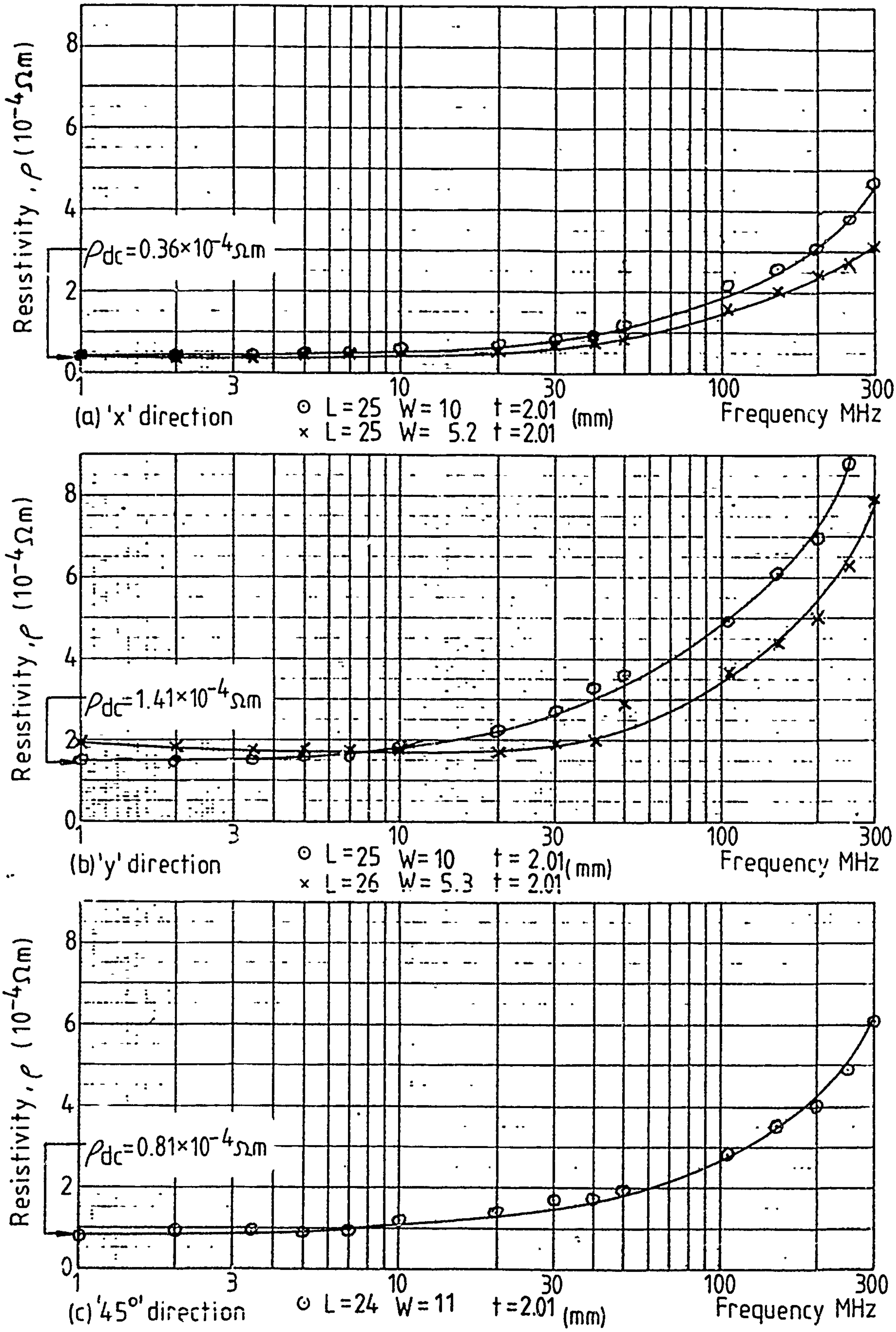
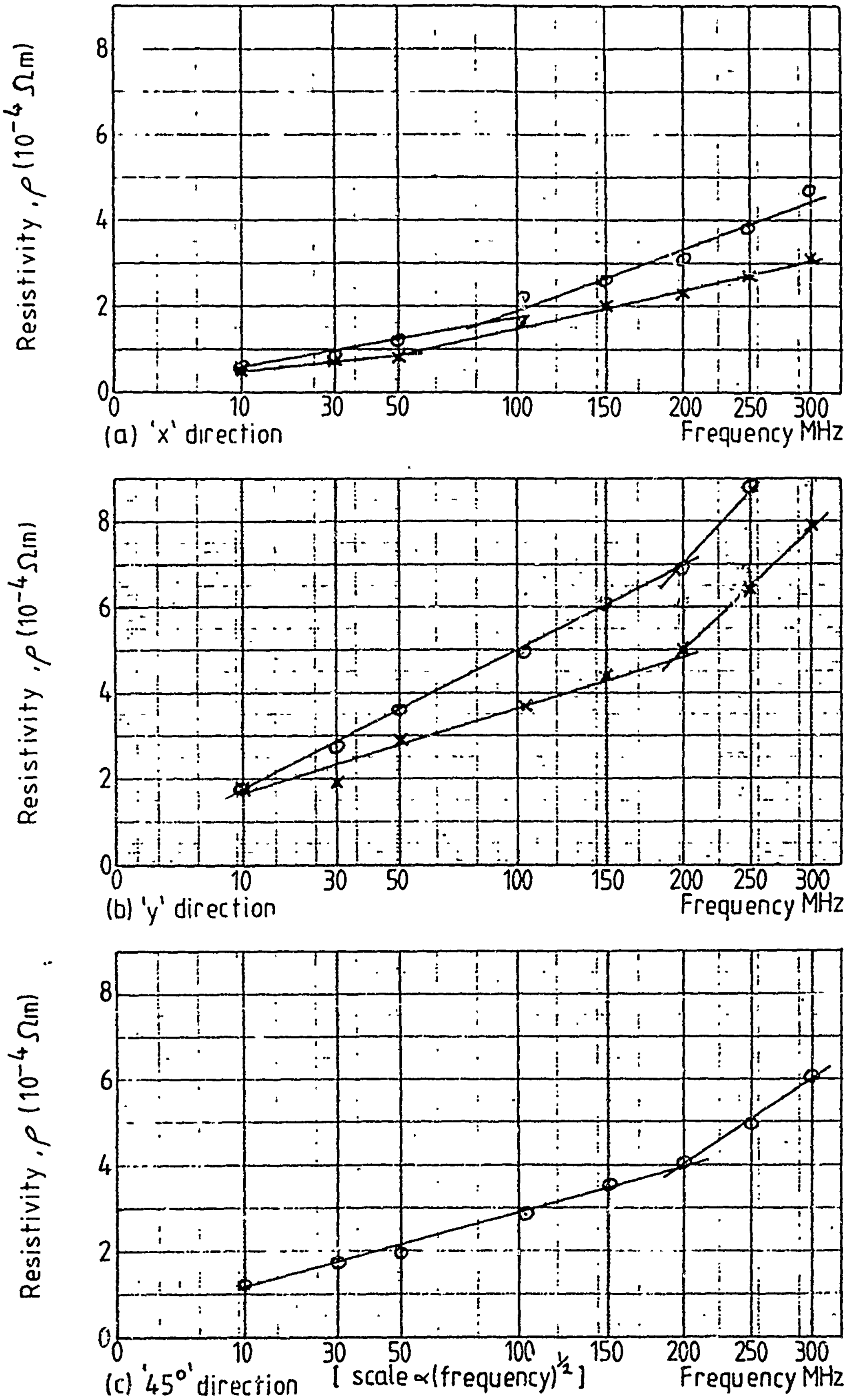


Figure 22 Resistivity-frequency characteristics for sample L



sample details in Fig. 22

Figure 23 Resistivity - frequency characteristics for sample L

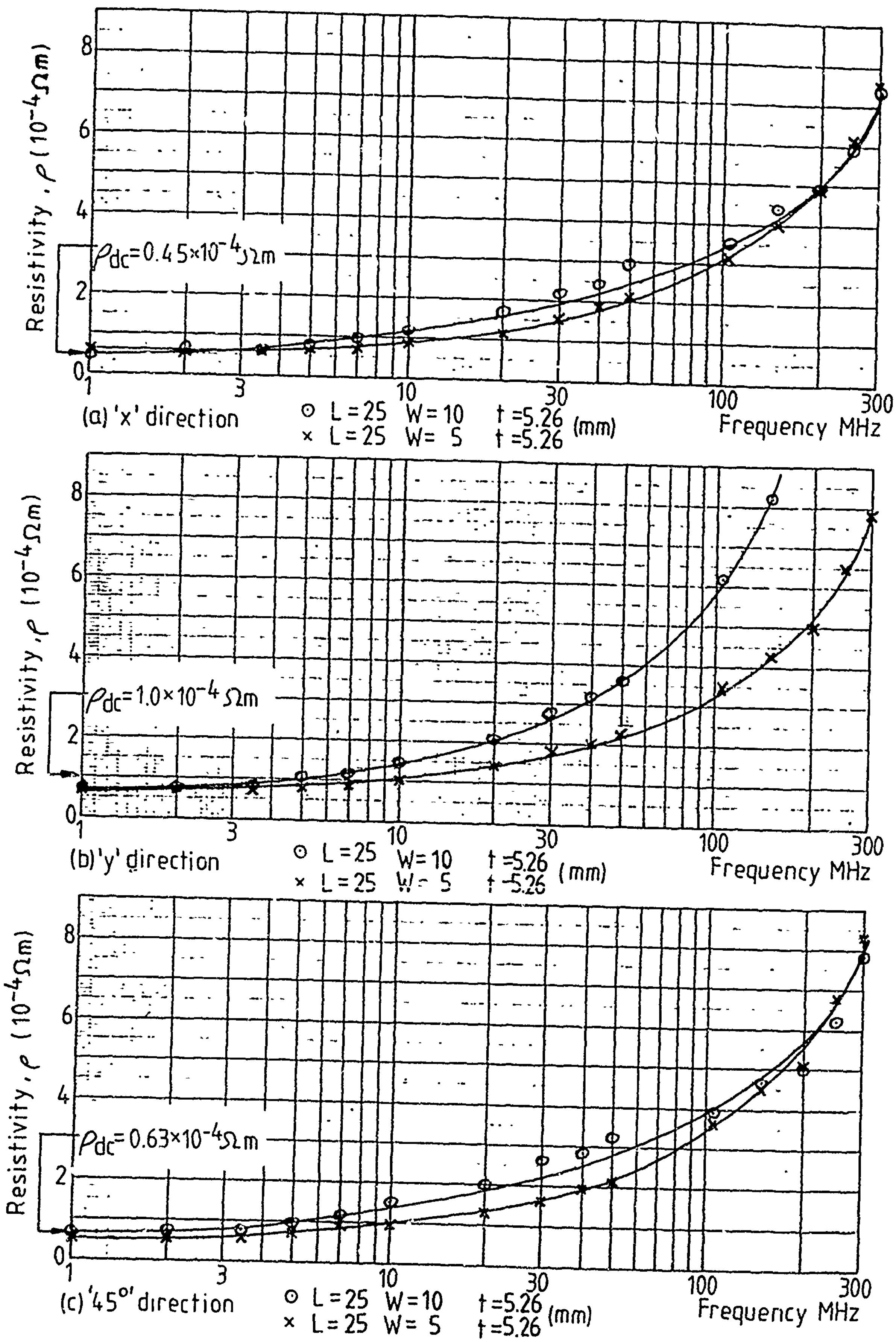
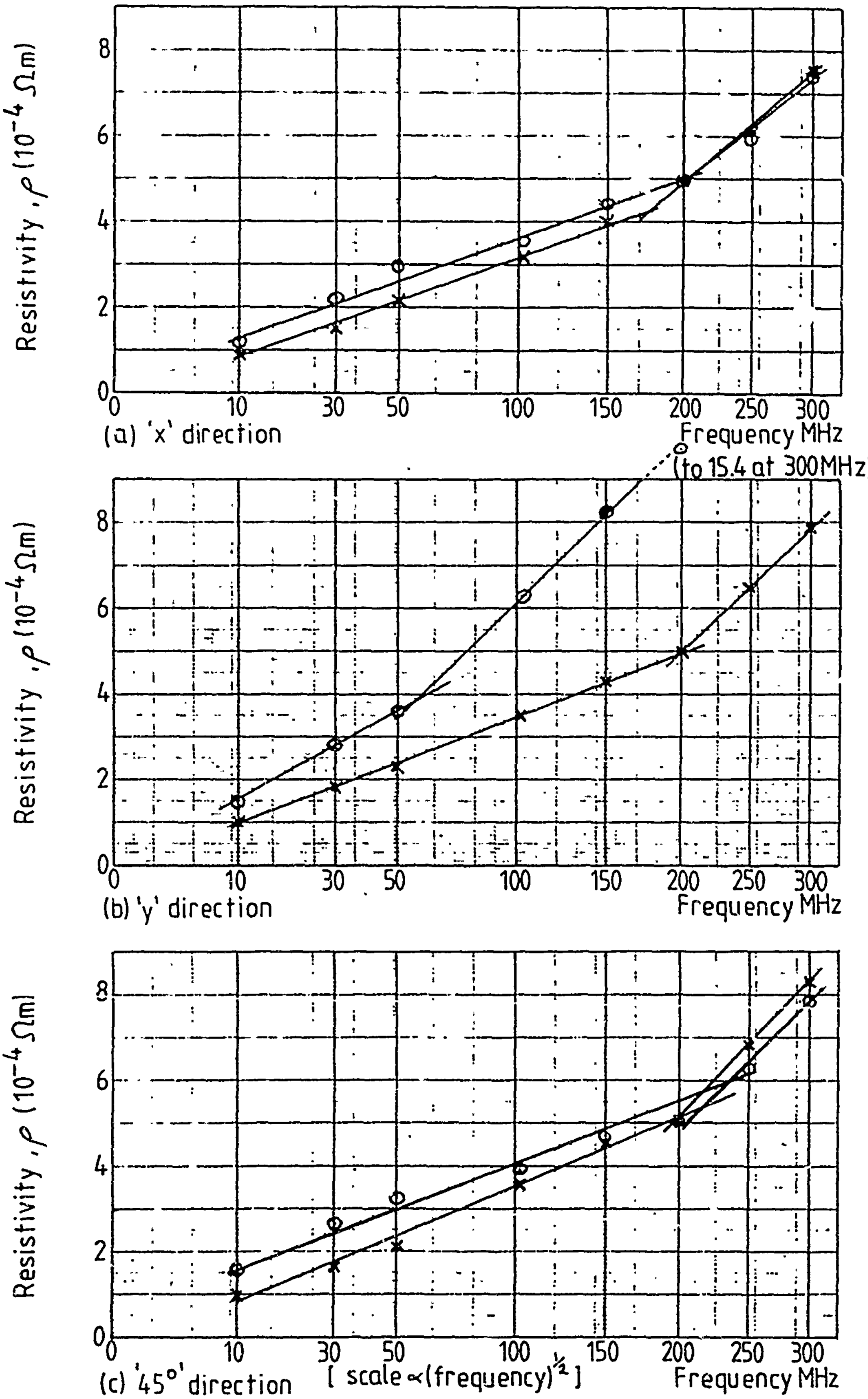


Figure 24 Resistivity-frequency characteristics for sample P5



sample details in Fig. 24

Figure 25 Resistivity-frequency charact°ristics for sample P5

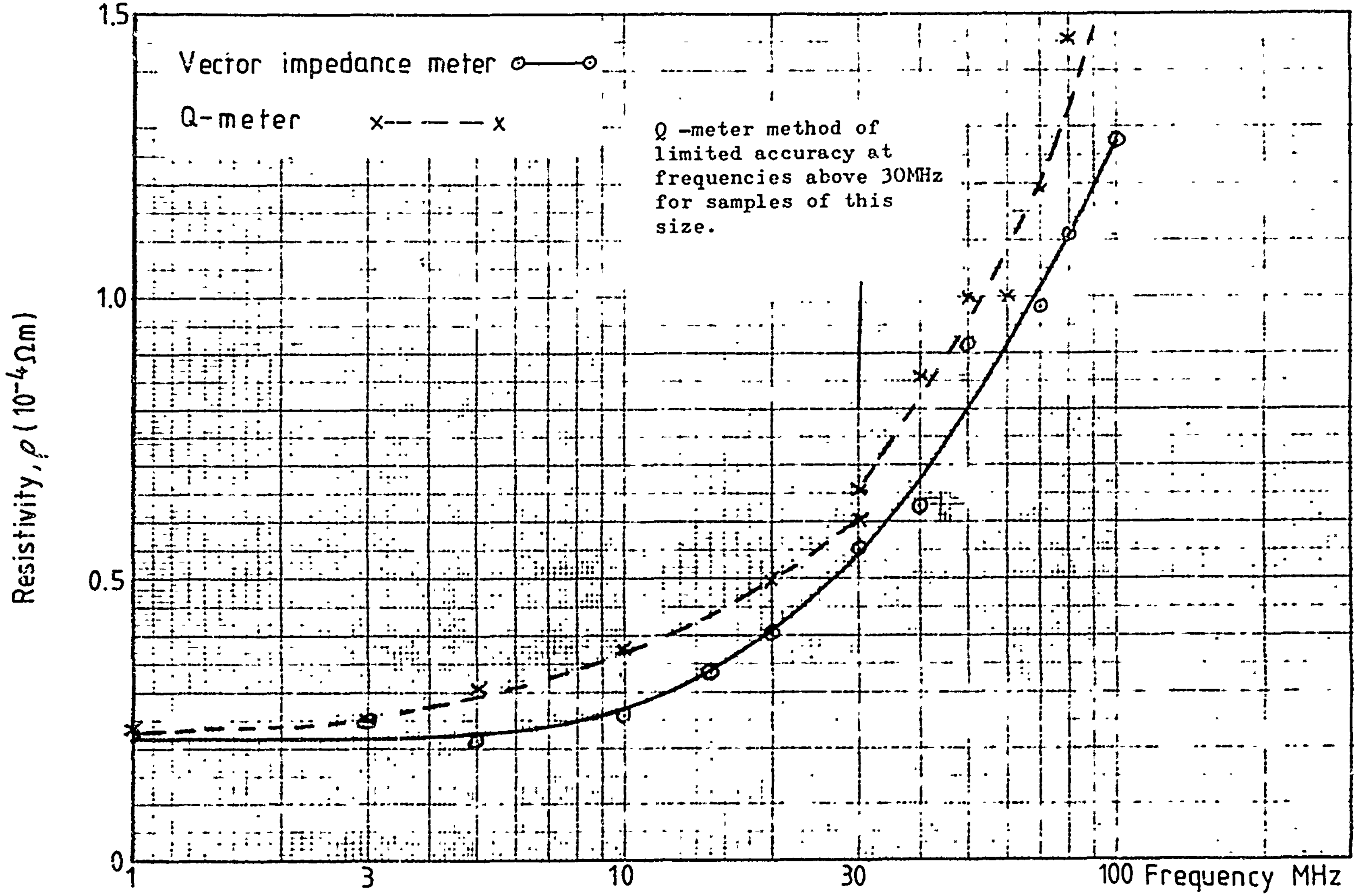


Figure 26 Transmission line sample H(y). Comparison of resistivity measurements by vector impedance meter and Q-meter methods

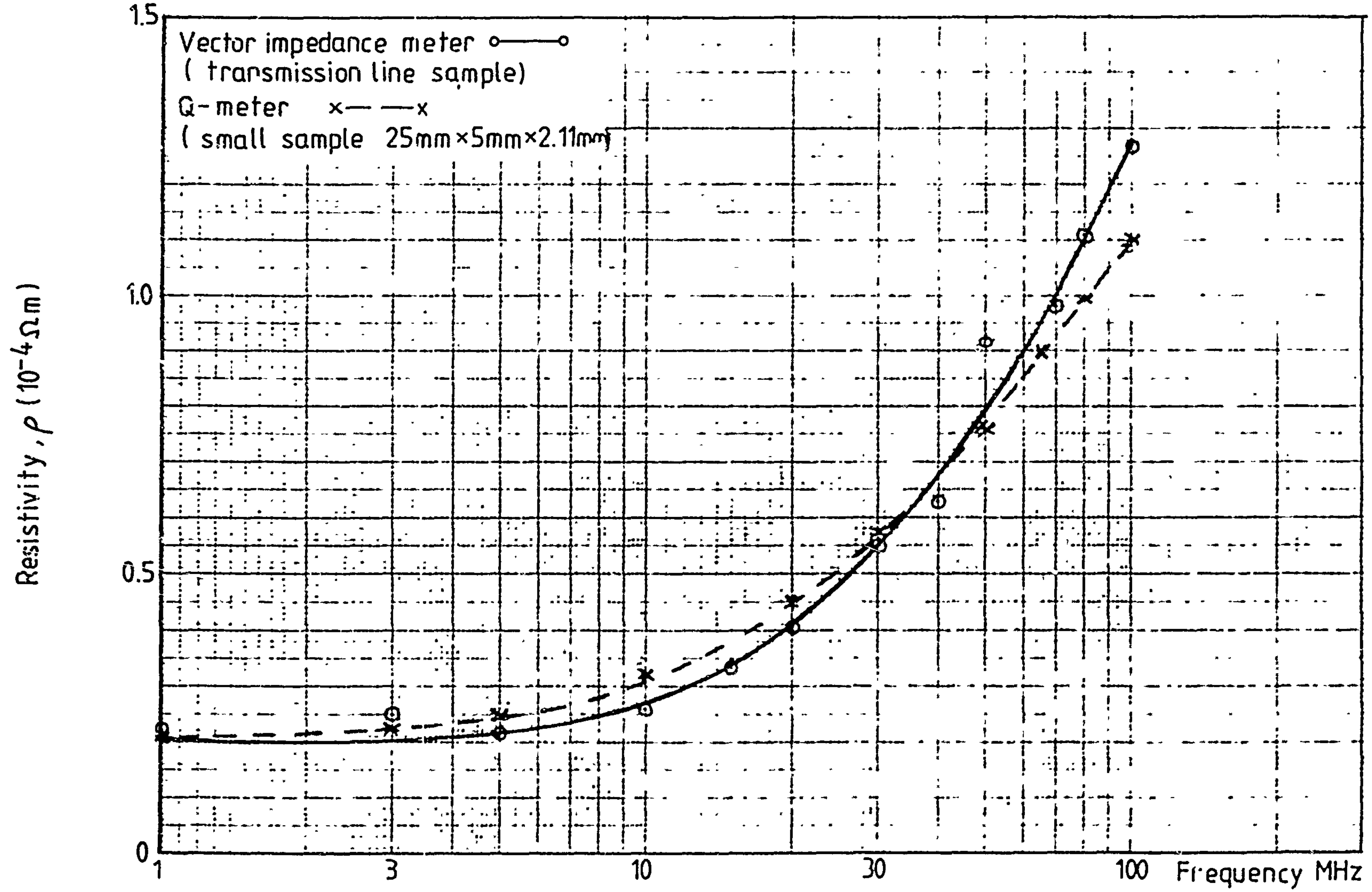


Figure 27 Comparison of resistivity measurements for transmission line and small samples of H(y)

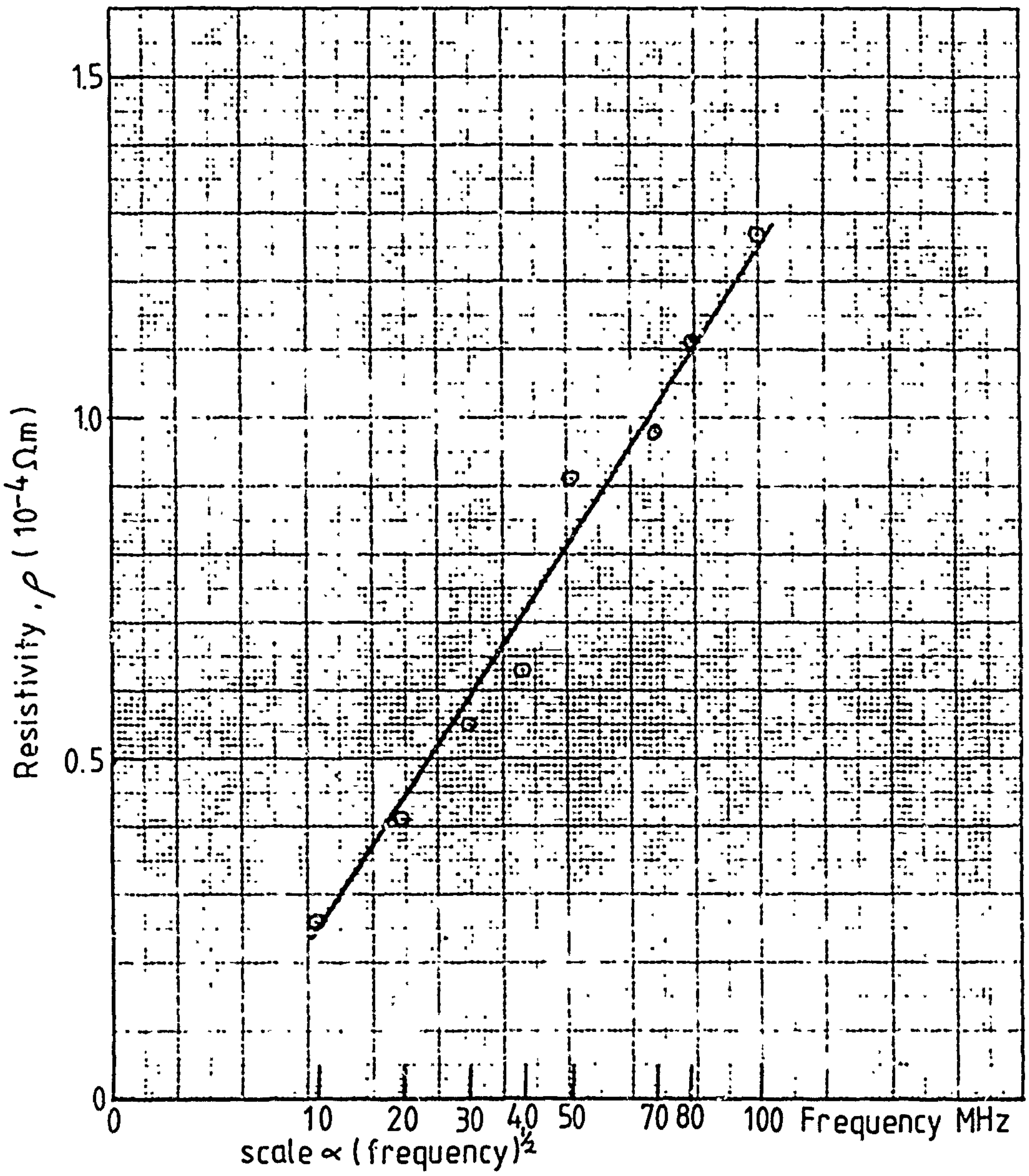


Figure 28 Transmission line sample H(y). Resistivity measurements by vector impedance meter plotted against (frequency)$^{1/2}$

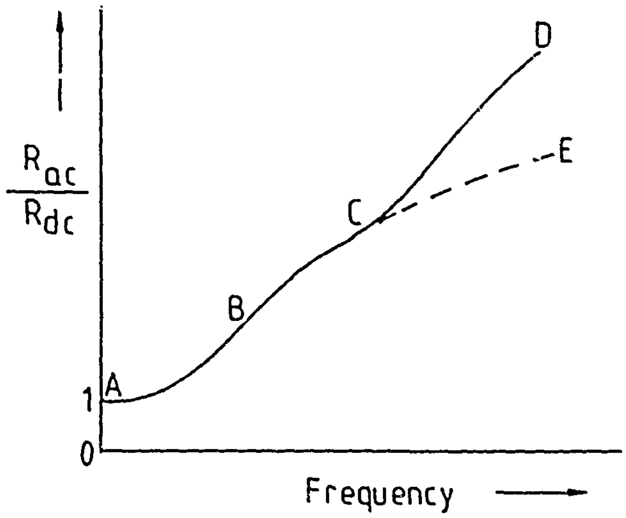
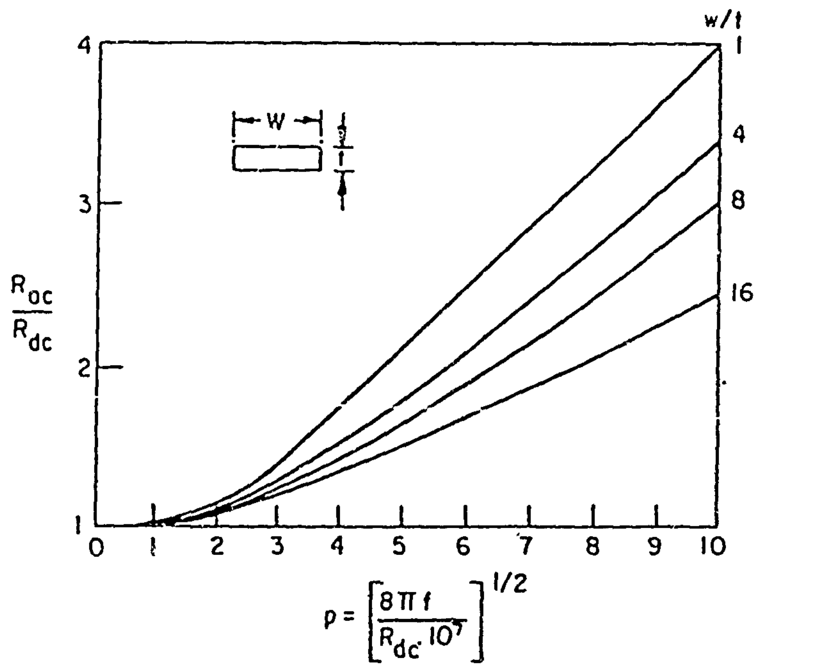


Figure 29 Qualitative relationship between R_{ac}/R_{dc} and frequency for rectangular cross-section (after Belevitch)



f = frequency in Hz

R_{dc} = resistance of conductor in ohms per metre (direct current)

Figure 30 Resistance ratio for conductor of rectangular cross-section in terms of parameter p (after Haefner)

APPENDIX

ELECTROLESS PLATING OF CFC SAMPLES

Sensitiser

Add 3.5 g $Sn Cl_2$ to 20 ml conc. HCl and add 5 ml of 1% $PdCl_2$.

Make up to 100 ml with distilled water.

The piece to be plated should be immersed at room temperature for about 5 minutes and then thoroughly rinsed (10 minutes).

Note: The sensitiser can be re-used.

Plating solution

35 g $CuSO_4 . 5H_2O$

170 g sodium potassium tartrate

50 g NaOH

Make up to 1 litre with distilled water.

Just prior to use, this solution (or part of it) should have added to it formaldehyde solution in the ratio of 100 mixture: 8 formaldehyde solution. The rinsed specimen should now be placed in this mixture and left until plated. Plating occurs best on rough surfaces (it does not adhere well to the smooth outer layer of resin). The resulting copper layer is readily soldered but overheating is to be avoided.

CHAPTER 3

MEASUREMENT OF THE EFFECTS OF LIQUIDS ON THE D.C. RESISTANCE OF CARBON FIBRE COMPOSITE MATERIALS

B W Smithers

SUMMARY

Water absorption to saturation has been found to increase the electrical resistance of samples by up to 40% for boiling tap water and 100% for boiling sea water. Protective fluid, hydraulic fluid, paraffin and sea water, all at room temperature, had little effect on the electrical resistance.

Woven cloth CFC material was unaffected by all the tests.

CONTENTS

1 INTRODUCTION

As part of the investigation into the rf properties of CFC materials, the effects of various fluids on the d.c. resistance of small samples of CFC were measured using simple four-terminal techniques.

It was originally agreed (ref. contract minutes 3320/M/3) that ERA would measure the d.c. resistance of water-saturated samples after these had been immersed in boiling water for several days. Results in this chapter refer to this method although it should be noted that it is now generally agreed (ref. contract minutes 3320/M/9) that boiling is neither a realistic nor satisfactory method of introducing water into CFC. RAE Structures Department have shown that room temperature methods are feasible and the Culham Lightning Studies Unit (CLSU) have been testing samples under such conditions.

2 TEST METHOD

The test samples were made up, as shown in Fig.1, from the same CFC materials that were used in the resistivity investigation of Chapter 2.

To measure the d.c. resistance, a current of 0.5 A was passed through the sample using the current terminals, and the voltage drop measured at the potential terminals by means of a digital voltmeter.

With all the fluids except sea water, the brass screws were attached to the samples and left in position at all times. Owing to the likelihood of corrosion of a brass/carbon combination when left in contact with sea water and the subsequent contamination of the fluid by metal ions, the screws were removed after pre-immersion measurements and re-attached to the sample after removal from the water for the purposes of measurement.

A further sample of E(x)* material with screws fitted permanently was immersed in sea water in a separate vessel.

2.1 Tap Water

In order to reduce the immersion time required to reach saturation it was recommended by RAE Materials Department that the samples should stand in boiling water for at least 72 hours. Boiling took place for 6 to 7 hours per day (except weekends), and totalled 79 hours, samples remaining immersed when not boiled. Total time of immersion was 672 hours.

* i.e. E material cut in 'x' direction.

2.2 Sea water

This was made up from a synthetic mix 'Instant Ocean' sea salt supplied by T Gerrard and Co. Samples were immersed for 429 hours at room temperature in a solution containing 37 g of salt per litre. This composition is said to conform to tropical sea water.

All the samples previously immersed in sea water at room temperature (without attached screws) were boiled in sea water until a total boiling time of 72 hours had elapsed. Voltage drops were noted at intervals during this treatment after removing samples from the immersant and attaching screws. Water loss was made good using distilled water.

The sample of material E(x) previously immersed in sea water at room temperature with screws attached was fitted with new screws and boiled in sea water separately from the screwless samples mentioned above. A total boiling time of 72 hours was given and voltage drop was noted at intervals during the treatment. Water loss was made good using distilled water.

2.3 Protective fluid

NATO code no.	C-634
Designation	PX24
Service ref. no.	34B/6850-99-224-4966
Specification no.	Def Stan 68-10/2

This fluid is an anti-corrosive material in common use and is a military version of 'WD 40'. Samples were immersed at room temperature.

2.4 Hydraulic fluid

Type	OM 15
DTD	585B
Service ref. no.	34B/9150-99-910-0572

Samples were immersed at room temperature.

2.5 Paraffin

Standard commercial grade ('Esso Blue').
Samples were immersed at room temperature.

3 RESULTS

3.1 Tap water

Figures 2 and 3 show the voltage drops in mV between the potential terminals at current of 0.5 A for the eight samples tested.

The voltage drops for most samples show a distinct tendency towards saturation after 30 to 40 hours' boiling. Seven samples showed significant increases in resistance over the 79 hours' boiling period. It is postulated that absorption of water resulted in swelling of the resin and a degree of separation of contact between the fibres. Resistance will, therefore, increase with absorption of water.

One sample, C(y), remained virtually unchanged over the whole test period. C(y) is a woven composite, and it is likely that the frequent inter-tow connections at the cross-overs in such a construction are resistant to separation by swelling of the resin.

3 1.1 Comparison of ERA and CLSU results

The work at Culham Laboratory, (ref 16) was carried out by boiling samples for 72 hours continuously, or by boiling samples during the day with a total boiling period of 70 hours and allowing them to cool over night whilst remaining immersed.

Additional tests were made to assess the effect of expelling moisture by prolonged heating of the samples in an oven. This work indicated that resistivity decreased as a result of water absorption and it has been suggested by CLSU that the electrical conductivity of the resin in their samples increased with the rise in water content.

Probably, the main differences in experimental technique between the ERA and CLSU tests were the methods of attaching current and voltage connections in the 4-terminal measurement method. CLSU used surface probes whilst ERA used drilled holes and screw connections.

3.1.2 The effect of reduced ambient air pressure

Six of the test samples boiled in tap water were re-measured for voltage drop after they had remained immersed in tap water at room temperature for a further 1392 hours after boiling ceased. They were then removed from the water and placed in a vacuum chamber at a pressure equivalent to an altitude of 70,000 feet (using altimeter) for a period of 15 hours. Voltage drops were measured after returning the samples to atmospheric pressure. Results are listed below:

Sample	Voltage drop (mV)	
	Before exposure	After exposure
D(y)	21.9	21.9
E(x)	15.2	15.2
G(y)	35.6	35.6
H(y)	21.0	20.9
I(y)	22.6	22.6
L(x)	26.2	26.1

No significant changes in voltage drop occurred as a result of this treatment. The samples were still noticeably damp even after spending 16 hours at this low ambient pressure (about 35 torr).

3.2 Sea water

Before testing after immersion, each sample was wiped with an absorbent cloth and brass screws and wires attached as shown in Fig.1.

Table 1 giving results for immersion at room temperature shows that some samples had voltage drops which varied slightly according to the direction of current flow. This effect was not always apparent, however, and may depend on the manner in which the screws make contact with the CFC on assembly.

The sample of E(x) material immersed at room temperature with screws fitted permanently also varied in its response to the direction of current flow.

Immersion in sea water at room temperature has had little effect on the voltage drops of the test samples. Some part of any variations may be due to small differences in the degree of contact obtained on reassembling the screws. No corrosion effects were noted for the sample E(x) permanently fitted with brass.

Table 2 and Figs.4 and 5 show the results for samples immersed in boiling sea water. Sample C(x), the woven material, has been virtually unaffected by this treatment but samples H(y), P5(y), for example, have final voltage drops which have increased by up to 100%. Once again, some small part of the changes could be due to variability of contact when reassembling screws.

The voltage drop of the sample E(x), with brass screws permanently attached increased by about 8% during the boiling sea water treatment. Corrosion of the brass screws was confined to the slotted faces of one group of three screws at the end of sample E(x). The effect was small and these slotted faces present a coppery appearance, in contrast to the dull brass appearance of the rest of the three screws, all the other screws, and the nuts and washers.

3.3 Protective fluid

The voltage drops and hence d.c. resistance of the samples have been largely unaffected by 1366 hours' immersion at room temperature. See Table 3.

3.4 Hydraulic fluid

The voltage drops of the samples have been largely unaffected by 697 hours' immersion at room temperature. See Table 3.

3.5 Paraffin

The voltage drops of the samples have been largely unaffected by 290 hours' immersion at room temperature. See Table 3.

4 CONCLUSIONS

Water absorption to saturation has been found to increase the electrical resistance of samples by 20% to 40% with the exception of a woven sample where no change in resistance occurred.

Immersion in protective fluid, hydraulic fluid or paraffin has had very little effect on electrical resistance.

Immersion in sea water at room temperature may be having a slightly greater effect than the protective fluid, hydraulic fluid or paraffin but some of this difference may be induced by the screw reassembly procedures.

Immersion in boiling sea water has increased the voltage drop of test samples by as much as 100%. The woven cloth material C(x) is unaffected by such treatment. The effect of boiling sea water on the sample of E(x) material with screws permanently fitted was somewhat less than that found for E(x) material with screws fitted only during measurement.

No significant changes in voltage drop were produced on subjecting water saturated samples to an ambient air pressure equivalent to an altitude of 70,000 feet for 16 hrs.

Table 1

Voltage drop (mV) for samples immersed in sea water

Sample	Elapsed time (hours)			
	0	70	239	429
C(x)	19.7	21.1	20.6	20.2
E(x)	9.9	9.2	11.5	10.1
F(y)	23.8	24.2-24.1*	24.3	25.6-25.7*
G(y)	29.5	29.8-29.7*	29.8-29.9*	30.3-30.4*
H(y)	15.1	13.5-13.3*	15.9	15.8-15.9*
I(x)	12.7	12.2	14.9	12.6
L(x)	12.9	14.8	14.3	16.3-16.4*
P5(y)	14.1	16.7-16.6*	14.6	15.9-16.0*
E(x)+	12.8	11.7-12.4*	12.6	12.3

* Values according to direction of current flow. (With no current in the samples all potential differences were recorded as 0.0000 V using the digital voltmeter).

\+ Sample had brass screws attached during immersion.

Table 2

Voltage drop (mV) for samples immersed in boiling sea water

Sample	Elapsed time (hours)			
	0	27	56	74
C(x)	20.2	20.0	20.5	19.9
E(x)	10.1	11.3-11.4*	12.7-12.8*	13.9
F(y)	25.6-25.7*	30.2-30.3*	33.6-33.7*	32.1
G(y)	30.3-30.4*	37.5	37.7	35.7-35.8*
H(y)	15.8-15.9*	27.4-27.5*	15.0-22.0+	28.7
I(x)	12.6	16.8-16.9*	14.9	21.3
L(x)	16.3-16.4*	22.8-22.9*	27.8-27.9*	21.9-22.0*
P5(y)	15.9-16.0*	29.9	35.4-35.5*	35.0
	0	18	35	72
E(x)$	14.0	14.4	14.6	15.1

* Values according to direction of current flow. (With no current in the samples all potential differences were recorded as 0.0000 V using the digital voltmeter).

\+ Unstable, irrespective of direction of current flow.

$ Sample had brass screws attached during immersion.

Note: Total times of immersion were:

Samples without screw fittings - 1050 hours.
Sample E(x) with screws - 2037 hours.

(Includes 429 hours noted in Table 1. Boiling of screwless samples started at 429 hours. Boiling of E(x) with screws started at 1602 hours).

Table 3

Voltage drop (mV) for immersed samples

Immersant	Sample	Elapsed time (hours)								
		0	22	46	214	358	478	646	1150	1366
Protective fluid	C(x)	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.7
	E(x)	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
	F(y)	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2
	G(y)	26.2	26.2	26.2	26.2	26.2	26.2	26.2	26.2	26.2
	H(y)	13.2	13.2	13.1	13.1	13.1	13.1	13.1	13.3	13.1
	I(y)	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9
	L(x)	14.1	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.1

Immersant	Sample	0	22	309	478	697
Hydraulic fluid	C(x)	15.3	15.3	15.3	15.3	15.3
	E(x)	8.3	8.4	8.4	8.4	8.4
	F(y)	22.7	22.7	22.7	22.8	22.8
	G(y)	25.8	25.7	25.7	25.7	25.7
	H(y)	14.5	14.5	14.6	14.6	14.6
	I(y)	12.7	12.7	12.7	12.7	12.6
	L(x)	14.3	14.3	14.3	14.3	14.1
	P5(y)	14.1	14.1	14.1	14.2	14.1

Immersant	Sample	0	69	290
Paraffin	C(x)	20.7	20.7	20.6
	E(x)	11.7	11.7	11.6
	F(y)	24.3	24.3	24.2
	G(y)	27.1	27.1	27.0
	H(y)	15.7	15.7	15.7
	I(y)	11.7	11.7	11.6
	L(x)	14.9	14.9	14.8
	P5(y)	13.0	13.0	12.9

all fittings are 8 BA brass

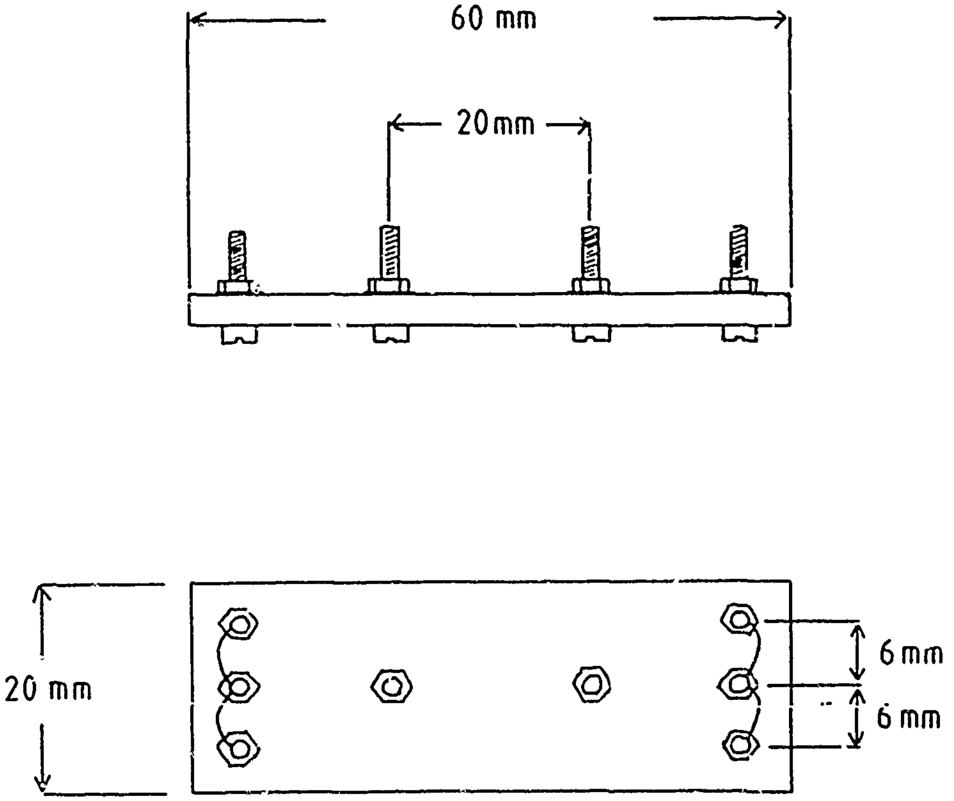


Figure 1 Test sample configuration

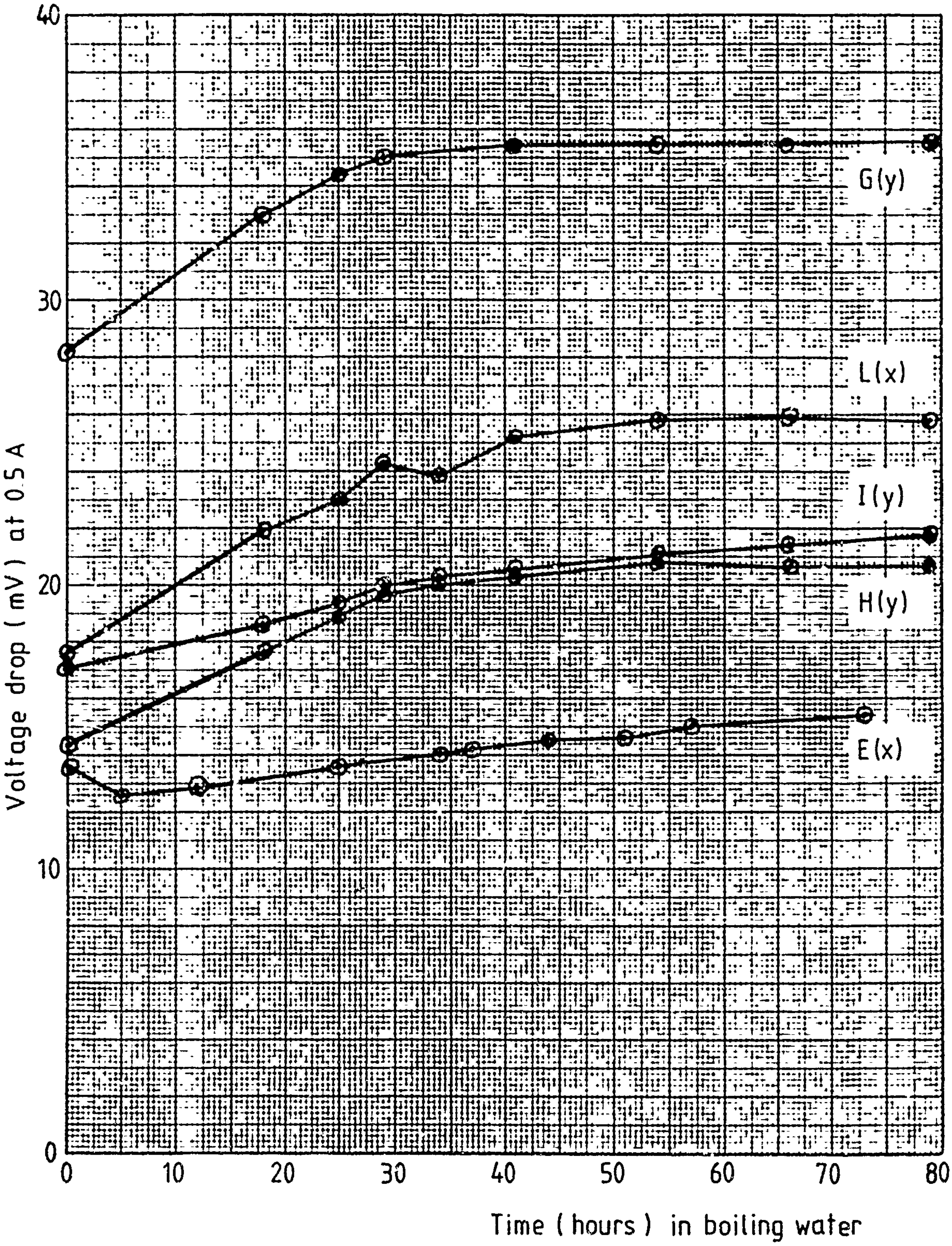


Figure 2 Immersion of CFC samples in boiling water

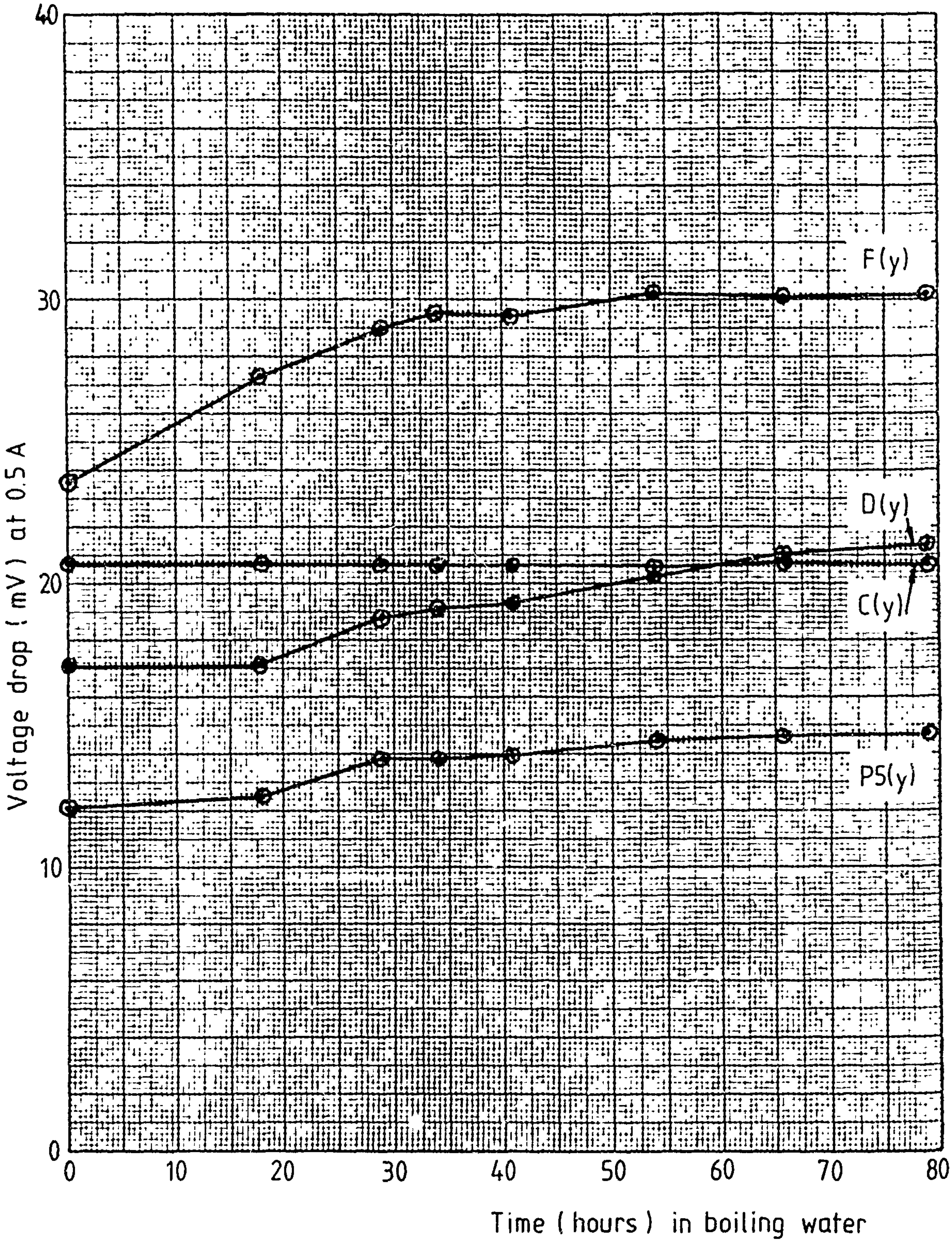


Figure 3 Immersion of CFC samples in boiling water

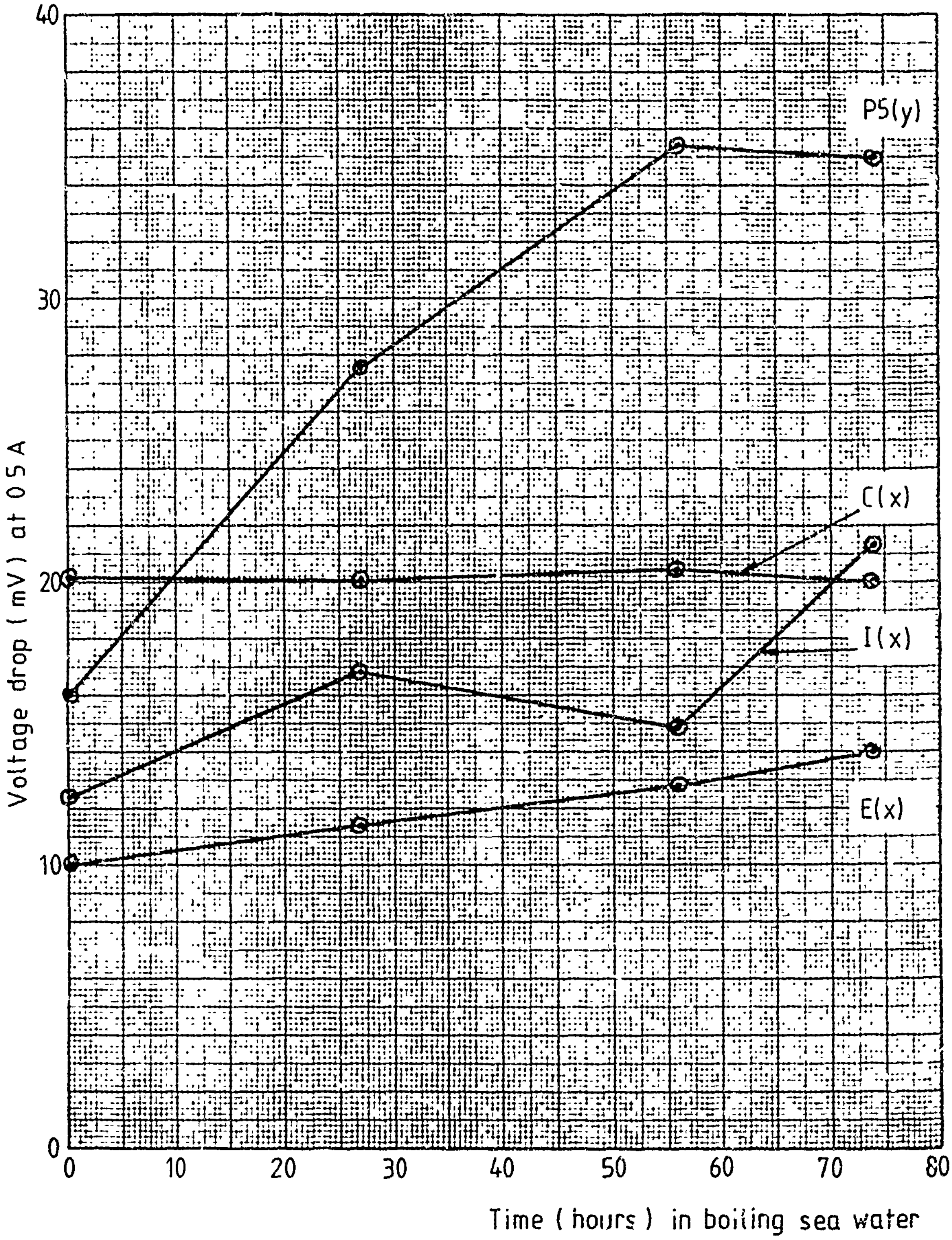


Figure 4 Immersion of CFC samples in boiling sea water

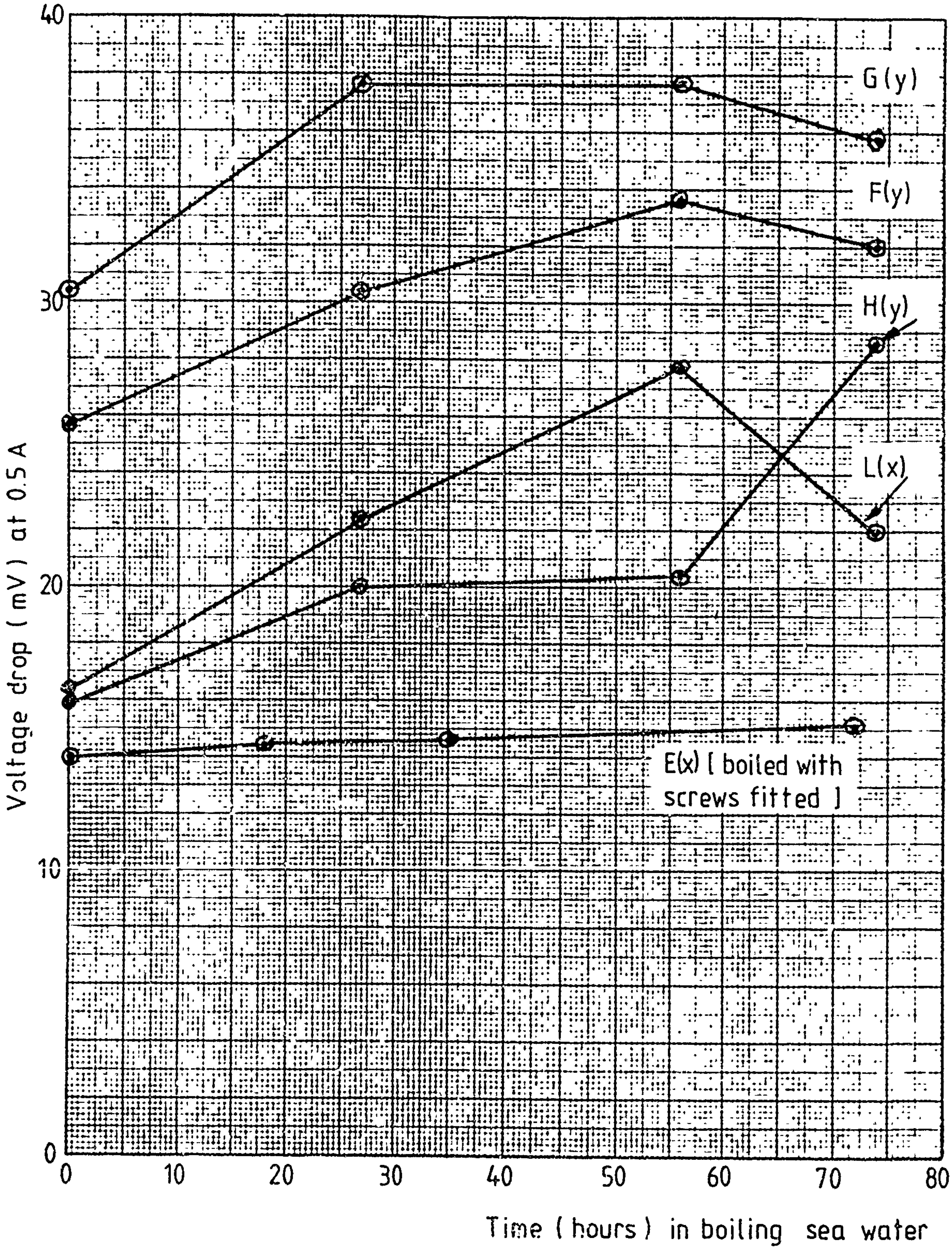


Figure 5 Immersion of CFC samples in boiling sea water

CHAPTER 4

MEASUREMENTS OF THE SCREENING EFFECTIVENESS OF CARBON FIBRE COMPOSITE MATERIALS

A McHale

SUMMARY

This chapter describes the techniques that were evolved to measure the screening effectiveness of a number of square CFC panels. Panels with various lay-ups and thicknesses were tested and the effects of different methods of jointing and mounting were also investigated.

Screening effectiveness to magnetic fields in the range 0.15-30 MHz and to electric fields in the range 30-1000 MHz has been measured.

These results represent the culmination of more than 2000 measurements taken over a three year period as the samples were made available.

CONTENTS

1 INTRODUCTION

Assessment of the screening effectiveness of any material should ideally be made on a complete enclosure constructed from the material. The enclosure should as far as possible be perfect in the sense that discontinuities in the joints and seams should be minimised. The limited availability of suitable CFC samples, however, dictated the use of an enclosure constructed partly from the test material and partly from material of greatly superior screening performance.

In the work described in this chapter, screening has been assessed using sample panels either 1 m square or 0.5 m square and the technique has been evolved to evaluate the screening effectiveness of the samples as part of a cubic enclosure.

In these investigations clear distinction is made between screening measured in the magnetic mode and in the electric mode, and to this end aerials designed to generate and respond to the respective modes have been used.

2 TEST PROCEDURE

2.1 The enclosure

Initially, five faces of 1 m cubic enclosure were constructed from 18 gauge aluminium sheets bolted to a 'Dexion' angle framework. The sixth face was left open to accommodate 1 m square test samples. Considerable effort was made to ensure that rf leakage through the joints and seams was minimised by the use of Eccoshield 'VY' conductive caulking compound. Tests showed, however, that the aluminium joints, although caulked, appreciably reduced the screening properties of the enclosure making it unsuitable for use in the present investigation and hence a second enclosure, shown in Fig.1, was constructed. The second enclosure was constructed from 26 gauge copper sheet which was folded around a supporting wooden framework. The joints were overlapped and soft soldered to ensure good electrical continuity. Five faces of the cube were copper and the sixth face (aperture) was edged externally with brass angle to provide a stable flat surface for attaching the test samples. The external dimension of this surface was arranged to be 1 m square so as to accommodate 1 m square

test samples. By allowing a 50 mm overlap for attaching the samples, the linear dimension of the square aperture and hence the depth of the cubic enclosure was 0.9 m.

Since an engineer was required to operate equipment from inside the enclosure during the magnetic mode measurements, the test samples were attached using 'Bulldog' clips which provided the required rapid access to the enclosure. 'Sticky Finger'* beryllium copper contact strips attached to the rim surface ensured optimum and repeatable electrical contact when interposed between sample and enclosure.

A number of the available samples were 0.5 m square and so a mask, Fig.2, was constructed from 10 gauge aluminium plate to reduce the aperture to 0.46 m square. This central aperture was edged with a brass rim and finger stock again ensured good electrical contact with the samples. The samples were clamped over the aperture with a second brass rim which was located on 0BA brass studding and secured with wing nuts. Brass spacers were included on the studding to prevent damage to the finger stock by overcompression.

2.2 Measurement techniques

To obtain the screening effectiveness of the CFC panels to both electric and magnetic fields, aerials were set up, one inside and one outside the copper enclosure. The transfer between the source and detecting aerials, through the aperture, was measured both with and without the test panels in position. Additional measurements were made with the aerials in free space.

Results were obtained for most samples in their original state as supplied to ERA, i.e. with the surface resin layer preventing good electrical contact to the fibres. Results were also obtained for the same samples after the fibres at the edges of one face had been exposed by removing the surface resin layer and then electroless plated by wiping the surface with the plating solution. This gave a copper border up to 50 mm wide (20 mm for the smaller samples) which ensured electrical contact between the carbon fibres and the enclosure. Further details on the electroless plating technique are given in the appendix to Chapter 2 of this report.

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*Instrument Specialities Company

2.2.1 Magnetic mode

Magnetic mode measurements were made over the frequency range 0.15-30 MHz. High ambient field levels over this frequency range were present in the laboratory and these would have obscured the signal from a source placed inside the enclosure and so the receiver was screened from these ambient levels by being installed within the enclosure.

The test configuration for the magnetic mode measurement is shown in Fig.1. The source of the magnetic field was a 0.25 m diameter loop, excited by a 5 W rf amplifier and an Advance SG200 signal generator. A 6 dB, 50 Ω attenuator, included between the amplifier and the loop, protected the amplifier output stage from impedance mismatch. The source loop was located outside the open face of the enclosure and the detector, a portable 'H' unit consisting of a 0.25 m diameter loop and a tuned pre-amplifier was located inside. The portable 'H' output was measured using a Schwarzbeck 1515 measuring receiver. Both equipments were battery powered and since the portable 'H' unit required tuning to each test frequency an engineer operated both the portable 'H' unit and the receiver from inside the enclosure making the detector equipment within the enclosure totally self-contained.

Within the enclosure, the receiver, battery pack and the operator were located behind the portable 'H' aerial. It was noted that a reduction in the received signal occurred at frequencies above 10 MHz if the operator moved within 0.1 m of the portable 'H' loop aerial. The presence of the operator behind the aerial in the enclosure did not otherwise noticeably affect the received levels, and indeed under open enclosure conditions the same level was measured whether or not the operator was inside the enclosure.

Measurements were made with the loops in a co-planar orientation and positioned along the axis of the open enclosure. This co-planar orientation is representative of the magnetic component of plane wave propagation towards the sample and polarised perpendicular to the line of propagation.

The loop external to the enclosure was excited at each test frequency and the signal received within the enclosure was measured with the portable 'H' unit. Maximum transfer for loops on the enclosure axis occurred when the detector was in the same orientation as the source. The centre-to-

centre separation between the loops was normally 1 m although some measurements were made at greater separations. The portable 'H' unit was located at the centre of the enclosure.

2.2.2 Electric mode

The test configuration for the electric mode screening measurements is shown in Fig.2. The screening measurements were made in the frequency range 30 MHz-1 GHz. Miniature bi-conical aerials were designed and constructed so as to give good sensitivity over the whole frequency range and this has given the capability of measuring screening of up to 100 dB throughout the range. Results were obtained with the bi-conical aerials separated by 0.5 m and equally displaced on each side of the enclosure aperture. The source aerial, excited by 5 W from an Ailtech power oscillator, was located inside the enclosure to preclude interference to radio services outside the laboratory. Stray radiation from the Ailtech unit was prevented by locating the unit, batteries and static inverter power supply in the aluminium enclosure to the rear of the copper enclosure. The excitation for the bi-conical aerial was then fed through adjacent 'N' type bulkhead connectors in both enclosures. A Singer NM 37/57 measuring set was used to measure the output from the detector aerial. It was necessary to introduce sheets of resistive material in the copper enclosure behind and to the sides of the aerial in order to damp the cavity resonances of this high Q enclosure.

3 RESULTS

Each sample was tested in both its original state and also after copper plating the borders. Results for an 18 gauge aluminium sheet have been included for comparison.

Details of the test samples are listed in Table 1. Four of the samples, P2-P5, were retested after these samples had undergone lightning tests. Details of these results are found in Appendix A, at the end of this chapter.

3.1 Definition of screening effectiveness

Let: V_{FS} = Signal transferred via the unobstructed path (free space)

V_B = Signal transferred in the presence of the open enclosure

V_{BT} = Signal transferred with the test sample installed

Screening effectiveness can be defined in two ways:

$$S_1 = V_{FS} - V_{BT} \qquad (1)$$

$$S_2 = V_B - V_{BT} \qquad (2)$$

When considering 0.5 m square samples V_B refers to the transfer in the presence of the open enclosure when fitted with the reduction mask.

The presence of the open enclosure did not affect the transfer in the frequency range 0.15-30 MHz, i.e. $V_B = V_{FS}$. The inclusion of the reduction mask decreased the transfer by some 7 dB throughout the 0.15-30 MHz range. Screening results in the magnetic mode therefore refer to Equation (2) thus separating the effects of the reduction mask from the CFC results.

In the electric mode the effect of the open enclosure on the transfer was small and tended to increase the transfer by reflection from the rear face of the enclosure. Below 100 MHz, however, the reflection from the rear of the enclosure was in antiphase with the direct propagation between the aerials thus reducing the transfer by as much as 33 dB at 70 MHz. CFC screening results calculated using Equation (2) would have shown a false minimum at 70 MHz due to the reduced transfer in the presence of the open enclosure, and so these results have been calculated using Equation (1).

3.2 Magnetic mode results

Magnetic mode screening results for all the available samples are listed in Table 2. Screening values are tabulated for frequencies of 0.2, 2.0 and 20 MHz both for the samples in their original state and also with copper plated borders ensuring low impedance contact to the sample.

Results for a number of samples are plotted in Figs.3-9. These curves show the general trend of all the results obtained. In several cases the screening was dependent on the sample orientation and two curves are given.

The loop transfer measurements were repeatable to ±1 dB. The maximum measurable screening effectiveness, limited by the portable 'H' sensitivity, was about 90 dB for a 1 m loop separation.

From the results obtained for the various samples, the effects of the following parameters have been noted.

3.2.1 Panel lay-up

Samples P3 and P4, with an asymmetric lay-up of 0°, 0°, 90°, 0°, exhibited different screening values for the two possible orientations. The greater screening occurred when the magnetic field was applied perpendicular to the lay of the majority of the fibres. Differences of 10 dB were typical throughout the range 0.15-30 MHz when low impedance contact was made to the sample edges. These differences were less when the samples were in their original state.

Sample A (0°, 90°) exhibited some directional properties, probably due to the two outermost tows lying in the same orientation, parallel to one of the edges.

Other samples had predominantly $\pm 45^{\circ}$ lay-up and no significant differences were noted for the remaining unjointed specimens.

3.2.2 Panel thickness

Results for samples P6 and P7, of similar construction, show the thicker P7 to have greater attenuation than P6. This is not an unexpected result.

3.2.3 Panel size

P9(a) and P9(b) were cut from the same sheet and can therefore be used to compare the two panel sizes. After copper plating the edges, the two panels give very similar results, Figs.3 and 4, the 1 m sample givin 2 dB more screening than the 0.5 m sample.

3.2.4 Effect of bonding the sample edges

In the original state the surface resin layers on the samples prevented any electrical continuity to the enclosure structure. This limited the screening to a maximum of 20 dB for the 1 m^2 samples. The same condition was simulated for an 18 gauge 1 m^2 aluminium panel by insulating the panel edges with paper masking tape. A similar maximum screening value was obtained, Fig.8, thus showing the poor screening throughout the frequency range to be limited by the integrity of the electrical bond to the panel edge. Also, at low frequencies, the screening is further reduced by the low conductivity of the CFC panels.

A considerable improvement in the screening effectiveness was obtained by exposing the fibre ends and electroless plating the sample edges. This gave a repeatable low impedance bond between each sample and the enclosure and an increase in the screening values of up to 20 dB at 2 MHz and generally more than 30 dB at 20 MHz.

3.2.5 Jointed panels

The screening effectiveness of three 1 m^2 jointed panels P10, P11 and P12 can be compared with the results for P9(a), a seamless panel of the same parameters. Three types of joints were investigated.

P10 - Butt jointed and bolted with 100 mm backing strip. (Bolts are at 50 mm pitch and bolt lines 50 mm apart.)

P11 - Lap jointed and adhesively bonded. The overlap was 25 mm.

P12 - Butt jointed and adhesively bonded with 100 mm backing strip.

Figures 3 and 5-7 show the screening for samples P9(a), P10, P11 and P12. For the jointed samples, curves are shown for the magnetic field applied both parallel and then perpendicular to the line of the joint both in the original state and with plated edges. The greater screening for each sample, in both the original and plated conditions, occurred when the field was applied perpendicular to the line of the joint.

For fields applied perpendicular to the line of the joint there was little difference between the jointed and seamless samples. For fields applied parallel to the line of the joint, the joint introduced an impedance

discontinuity in the path of the current induced in the sample and the screening was reduced accordingly. Some conductivity was maintained through the bolts for P10 and through limited contact between exposed fibres in the milled overlap for P11. Further continuity in P11 was precluded by the use of non-conducting adhesive. There was no continuity across the butt joint of P12 and the resulting screening was significantly less than for the seamless sample.

Sample P8 was initially measured before it was cut in half and reassembled using an adhesively bonded butt joint with backing strip. Results in Table 2 show the screening to be significantly reduced by the joint.

3.2.6 Method of mounting panels

The electroless plating method is ideal in the laboratory for optimising the electrical continuity across joints between the samples and the enclosure but is unsuitable for use in airframe manufacture. Three samples, P13-15, each 1 m^2 4 ply with a 60 mm border built up to 24 ply, were attached to aluminium 'picture frames' (1 m^2 x 60 mm x 10 gauge) using adhesive bonding, bolting and riveting techniques. The 'picture frames' were then attached to the enclosure in the usual way.

P13 was adhesively bonded by Materials Department at the Royal Aircraft Establishment. P14 was bolted using 5 mm diameter titanium bolts with a countersunk angle of 100°, 28 mm pitch and cadmium plated steel nuts. P15 was riveted using Avdel 0.125 in. stainless steel 4051-0411 self-plugging rivets pitched at 25 mm. The results for these three samples are compared in Fig.9. The riveted and bolted samples gave similar results and exhibited significantly greater screening than the adhesively bonded sample.

The screening results for these panels are also compared, in Chapter 7 of this report, with results obtained for similar CFC panels which were mounted, using the same techniques, on a Wessex helicopter ground-experimental-vehicle.

3.3 Electric mode results

The transfer measurements between the bi-conical aerials were generally repeatable to within ±2 dB and it was possible to measure values of

screening effectiveness up to 120 dB at frequencies between 150 MHz and 1 GHz. It should be noted, however, that the screening effectiveness of the 'Sticky Finger' contact strips is quoted by the manufacturers to be 117 dB at 400 MHz and 104 dB at 1 GHz which may result in measurement limitations where the screening effectiveness is greater than 100 dB. Below 150 MHz the reduced sensitivity of the bi-conical aerial lowers the limit of measurement to 100 dB.

Although the inclusion of the damping material much reduced the 'Q' of the enclosure, reflections within the enclosure affected the measurements for the 0.5 m^2 samples where impedance discontinuities exist between the mask and the original state samples. These imperfections and the geometry of the enclosure caused some reductions in the screening around 100 MHz and also between 200 MHz and 300 MHz. Results for the 1 m^2 samples and the plated 0.5 m^2 samples were less affected but fluctuations still existed over the frequency range which made the comparison of the different panels difficult, and therefore the results for each panel have been 'smoothed' according to the formula given in Appendix B at the end of this chapter. These modified results, at four representative frequencies in the 30-1000 MHz range, are listed in Table 3. In addition, Figs.10-16 show the screening for selected samples over the whole frequency range, and also serve to indicate the general form of the 'E' field results. The measured values generally fluctuated within ±8 dB of these smoothed curves.

From the results obtained for the various samples, the effects of the following parameters are noted.

3.3.1 Panel lay-up

Samples P3 and P4 exhibited some directionality to the applied electric field with differences in screening values for the two possible panel orientations of up to 17 dB for P3 and up to 9 dB for P4. There was no significant directionality for the samples in their original state.

3.3.2 Panel thickness

The 20 ply sample P7 gave some 10 dB more screening in the plated state than the thinner P6. In the original state there was no more than 2 dB difference between the panels.

3.3.3 Panel size

Figures 10 and 11 compare samples P9(a) and P9(b). Results are similar in the original state. In the plated condition, the 0.5 m^2 sample gave the greater screening by up to 10 dB, although the integrity of the fingerstock appears to reduce the screening above 500 MHz. The greater screening for the 0.5 m^2 sample is probably an effect of the reduction mask although the transfers measured through the open enclosure with and without the open mask were very similar.

3.3.4 Effect of bonding the sample edges

Copper electroless plating the sample edges ensured an optimised low impedance bond between the enclosure and the samples. This increased the measured screening values by 40-50 dB throughout the 30-1000 MHz range for most panels.

3.3.5 Jointed panels

The jointed panels exhibited directional screening properties. Figures 12-14 show screening curves for the 'E' field applied both perpendicular and then parallel to the line of the joint and also in both the original state and after plating the border. Maximum screening in the plated state occurred for the 'E' field applied parallel to the joint. In this orientation, the bolted P10 gave similar screening to the seamless P9(a), Fig.10, over much of the frequency range. Values of screening obtained for the adhesively bonded panels P11 and P12 were generally 5 dB less than those obtained for P9(a).

For 'E' field applied perpendicular to the joints the screening was significantly reduced. The bolted joint at P10 reduced the screening by as much as 30 dB, the lap joint of P11 by as much as 38 dB and the butt jointed P12 by as much as 46 dB below the values for the seamless P9(a).

3.3.6 Method of mounting panels

Figure 15 shows the screening performance for an aluminium panel mounted on the enclosure. Values of 110-130 dB were measured : these were limited by the performance of the fingerstock. Results are also shown for this panel insulated from the enclosure using paper masking tape. This simulated low conductivity joint reduced the screening performance to less than 50 dB.

Figure 16 compares the screening for panels P13-P15 Below 600 MHz these three panels gave similar results, i.e. 62-70 dB screening. Above 600 MHz the riveted sample gave the greatest screening, some 10 dB more than for the bolted sample and 16 dB more than for the adhesively bonded sample.

4 CONCLUSIONS

This chapter has presented a factual description of the experimental work which has been performed to determine the screening effectiveness of several samples of carbon fibre composite materials. Ideally, screening should be assessed for an enclosure constructed entirely from the material under test and any other method is necessarily a compromise. The techniques adopted for this investigation were evolved mainly to cater for sample sizes which were readily available.

The carbon fibre composite samples which have been examined are inherently capable of providing relatively high attenuation in the electric mode over a wide frequency range. The values of attenuation in the electric mode for a number of samples are close to the upper limit of measurement which is determined by available power in the transmitter and sensitivity of the receiving installation.

The attenuation in the magnetic mode falls with decreasing frequency in the range below 30 MHz and may be no more than 10-20 dB below 1 MHz. These values refer to the inherent capability of the material as part of the test configuration. It is evident from the results on samples in both their original condition and after plating the sample edges, and also from the results for the various jointed samples, that significant degradation of screening performance will occur if precautions are not taken to achieve satisfactory electrical contact at the joints.

Table 1

Identification of test samples

ERA Designation	Dimensions m	No. of plies	Fibre type	Resin	Lay-up	Source	Other detail
A	1.0 x 1.0	16	-	Phenolic	0°, 90°	RAE	Electroplated by the RAE
P1	0.5 x 0.5	16	XAS	BSL 914C	±45°	BAe	Identical samples
P2	0.5 x 0.5	16	XAS	BSL 914C	±45°	BAe	
P3	0.5 x 0.5	4 each skin	XAS	BSL 914C	0°, 0°, 90°, 0°	BAe	Hexel HRP 3/16 in. cell 1 in. thickness infill
P4	0.5 x 0.5	4 each skin	XAS	BSL 914C	0°, 0°, 90°, 0°	BAe	Aluminium ¼ in. cell 1 in. thickness infill
P5	0.5 x 0.48	40	HM	Code 69	Quasi isotropic i.e. 5 x (90°, 45°, 0°, -45°, -45°, 0°, 45°, 90°)	BAe	Supplied with notch (15 mm x 10 mm) cut into longer side
P6	0.95 x 0.95	14	XAS	BSL 914	45°, 135°, 2 x 0°, 90°, 2 x 0°: mirror	BAe	Difficult to plate using electroless techniques
P7	0.95 x 0.95	20	XAS	BSL 914	45°, 135°, 4 x 0°, 45°, 135°, 0°, 90°: mirror	BAe	
P8	0.5 x 0.5	16	XAS	BSL 914C	4 x (2 x 45°, 2 x 135°)	BAe	Originally supplied whole subsequently halved and butt jointed by BAe using backing strip and adhesive bonding
P9(a)	1.0 x 1.0	16	XAS	BSL 914C	±45°	RAE	Taken from seamless panel P9, 1.5 m x 1.0 m
P9(b)	0.5 x 0.5	16	XAS	BSL 914C	±45°	RAE	
P9(c)	0.5 x 0.5	16	XAS	BSL 914C	±45°	RAE	
P10	1.0 x 1.0	16	XAS	BSL 914C	±45°	RAE	Butt-jointed bolted with backing strip
P11	1.0 x 1.0	16	XAS	BSL 914C	±45°	RAE	Lap-jointed and adhesively bonded
P12	1.0 x 1.0	16	XAS	BSL 914C	±45°	RAE	Butt-jointed adhesively bonded with backing strip
P13	1.0 x 1.0	4	XAS	BSL 913	±45°	WHL	Adhesively bonded to Al picture frame
P14	1.0 x 1.0	4	XAS	BSL 913	±45°	WHL	Bolted to Al picture frame
P15	1.0 x 1.0	4	XAS	BSL 913	±45°	WHL	Riveted to Al picture frame

Table 2

Magnetic screening effectiveness of CFC panels

Sample	Screening effectiveness (dB)						Comments
	Original state			Copper plated borders			
	0.2 MHz	2.0 MHz	20 MHz	0.2 MHz	2.0 MHz	20 MHz	
A	11 9	27 23	46 40	25 24	43 42	72 70	Two orientations
P2	4	15	25	16	34	61	
P3	3 2	16 10	32 26	12 4	31 21	60 47	Two orientations
P4	6 4	18 13	25 24	13 6	31 21	50 41	Two orientations
P5	9	19	31	29	55	75	
P6	6	14	16	11	30	51	
P7	8	15	18	16	36	63	
P8	4	16	33	13 11 4	33 30 15	53 56 26	Seamless Joint vertical Joint horizontal
P9(a)	8	19	13	19	39	67	
P9(b)	3	15	24	17	37	64	
P10	8 6	19 18	13 13	20 17	40 36	70 63	Joint vertical Joint horizontal
P11	8 5	19 12	18 13	18 13	39 33	66 56	Joint vertical Joint horizontal
P12	7 4	18 14	15 14	18 6	39 19	67 30	Joint vertical Joint horizontal
P13	-	-	-	4	21	29	Adhesively bonded
P14	-	-	-	10	29	49	Bolted
P15	-	-	-	10	29	48	Riveted
Aluminium 18 gauge	19*	21*	19*	68+	86+	>97+	*Edges insulated with masking tape +Standard aluminium

Table 3

Electric screening effectiveness of CFC panels

Sample	Screening effectiveness (dB)								Comments
	Original state				Copper plated borders				
	50 MHz	120 MHz	300 MHz	900 MHz	50 MHz	120 MHz	300 MHz	900 MHz	
A	50	49	46	51	97	107	120	112	
P2	52	44	42	53	101	102	102	97	
P3	50 49	46 46	55 54	52 51	94 82	93 81	88 73	91 74	Two orientations
P4	47 47	40 39	44 43	52 52	82 74	87 78	86 80	79 76	Two orientations
P5	47	40	39	50	104	107	110	108	
P6	49	47	46	54	83	82	76	73	
P7	50	49	48	55	92	92	87	87	
P8	63	61	66	70	89 85 40	84 81 44	89 82 52	87 74 57	Seamless Joint vertical Joint horizontal
P9(a)	61	54	55	74	97	99	100	107	
P9(b)	54	53	54	60	103	106	111	99	
P10	60 60	58 55	62 57	72 66	106 86	102 77	100 73	94 74	Joint vertical Joint horizontal
P11	65 55	54 52	57 54	69 63	98 65	94 61	95 66	99 74	Joint vertical Joint horizontal
P12	54 47	51 47	53 51	64 59	94 53	94 54	95 59	96 63	Joint vertical Joint horizontal
P13	-	-	-	-	63	64	69	59	Adhesively bonded
P14	-	-	-	-	68	65	65	65	Bolted
P15	-	-	-	-	70	66	66	76	Riveted
Aluminium 18 gauge	48*	48*	45*	53*	113+	122+	125+	114+	*Edges insulated with masking tape +Standard aluminium

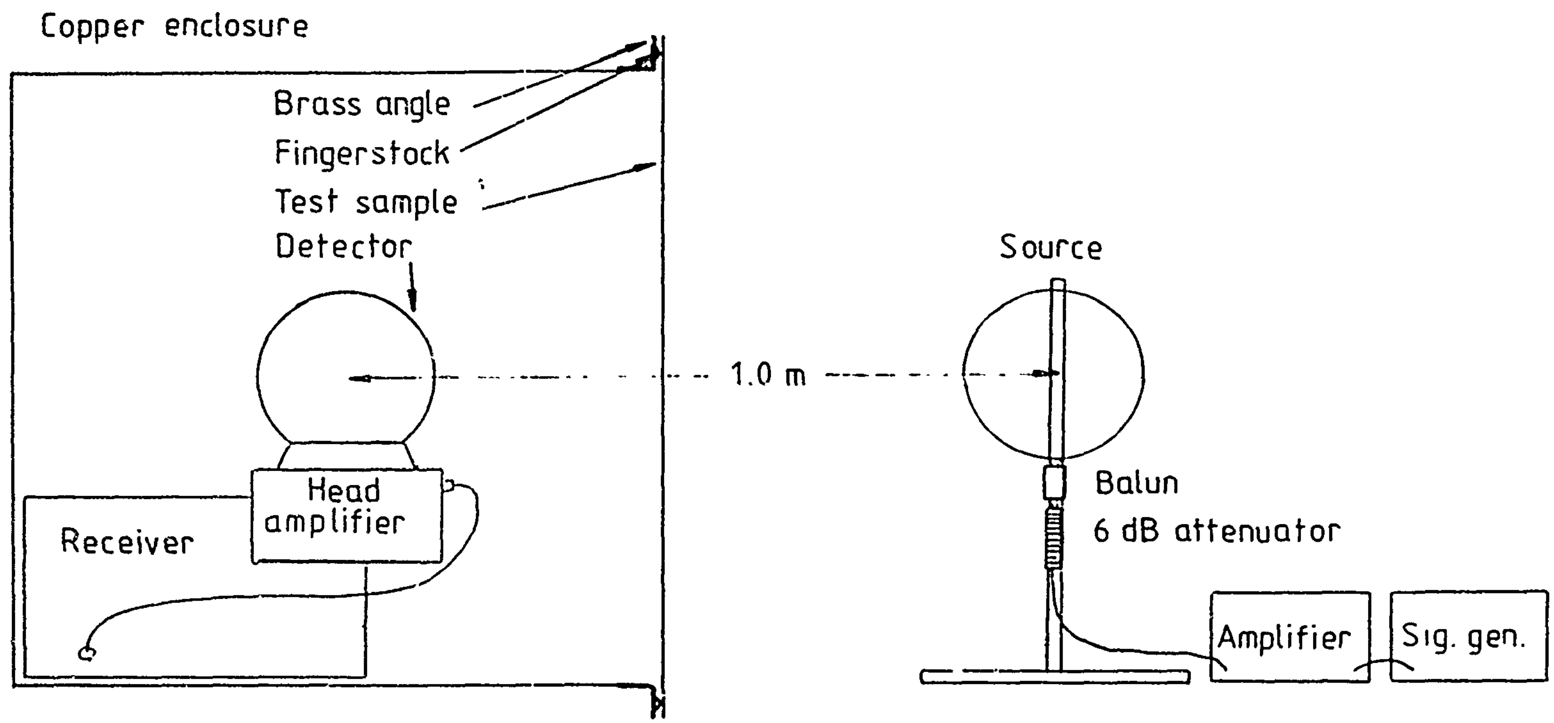


Figure 1 Test configuration for magnetic screening measurements

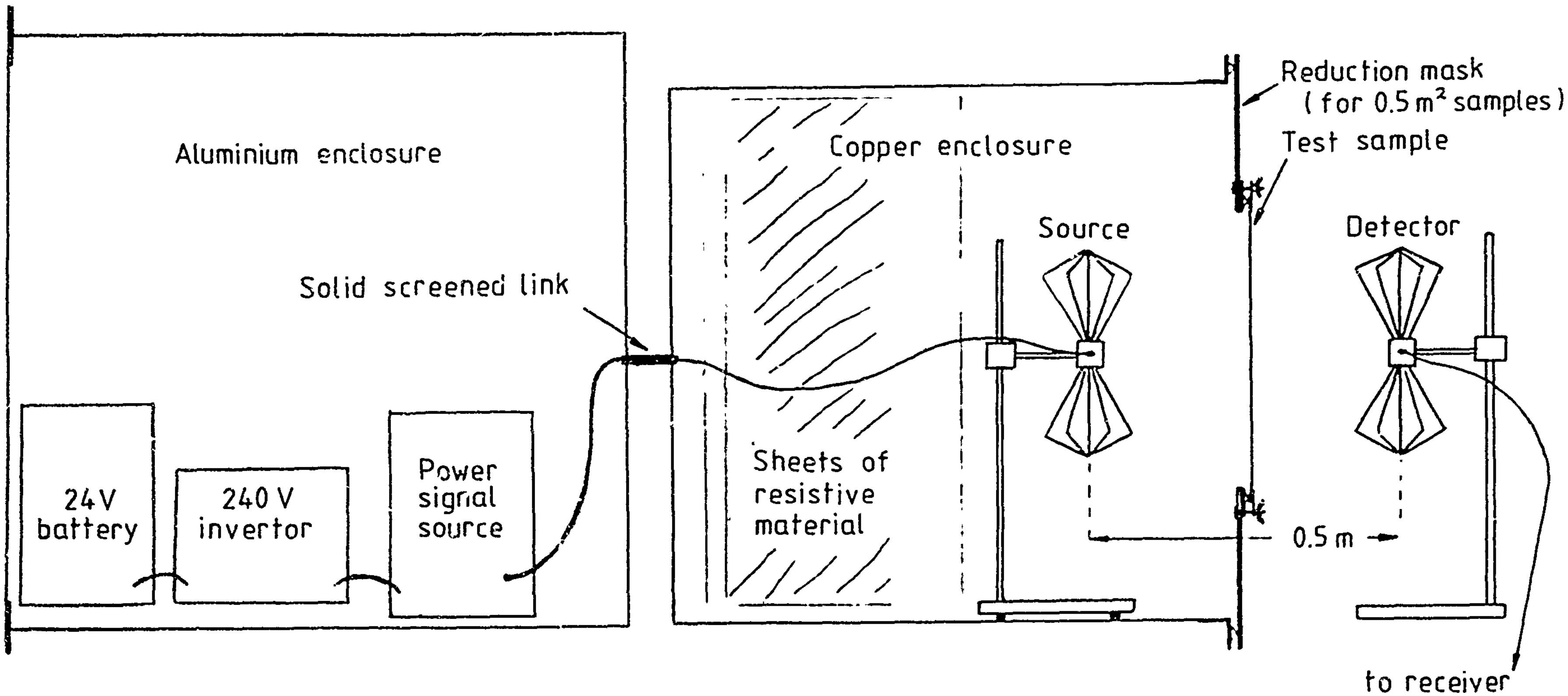


Figure 2 Test configuration for electric screening measurements

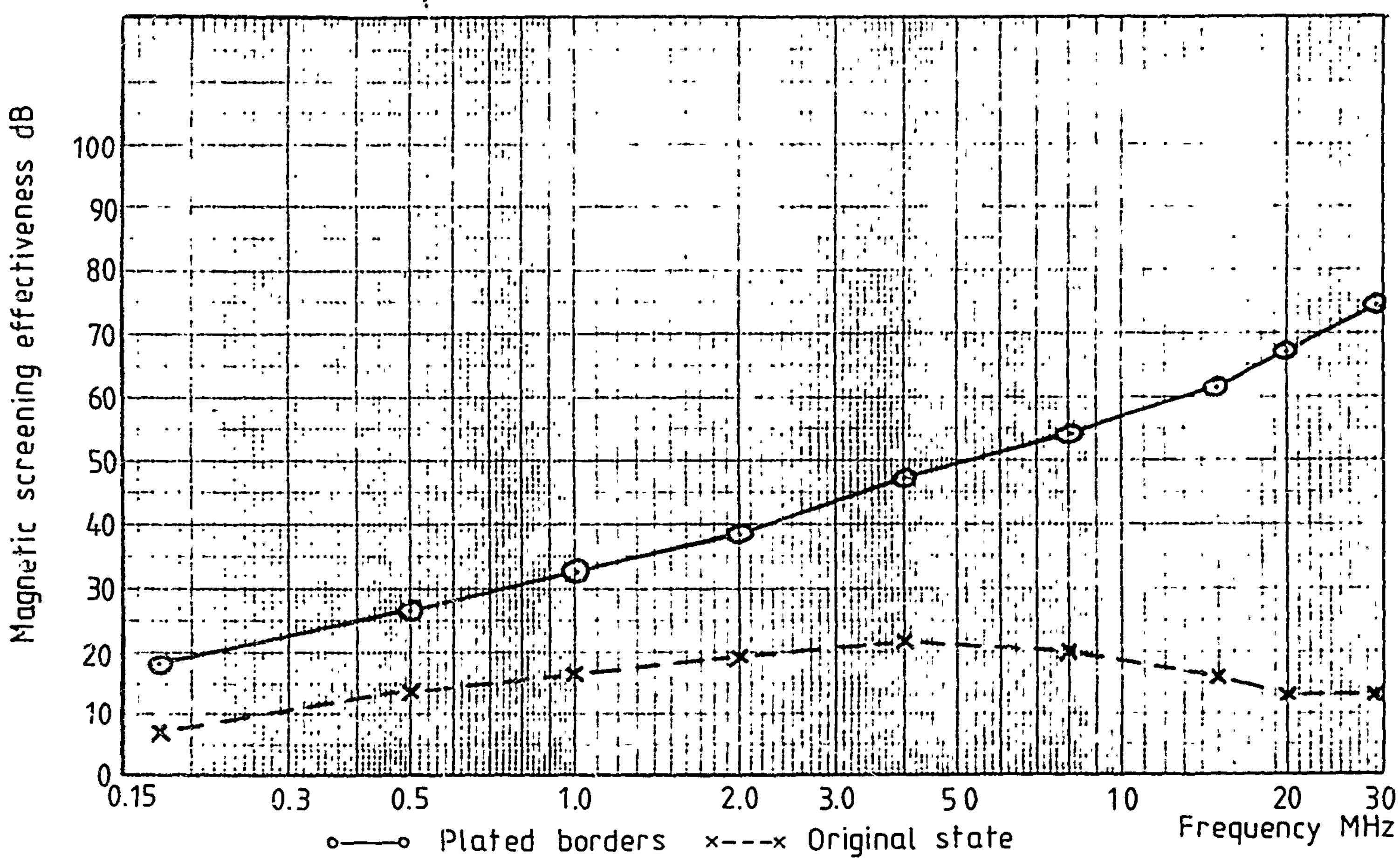


Figure 3 Magnetic screening effectiveness - sample P9(a)

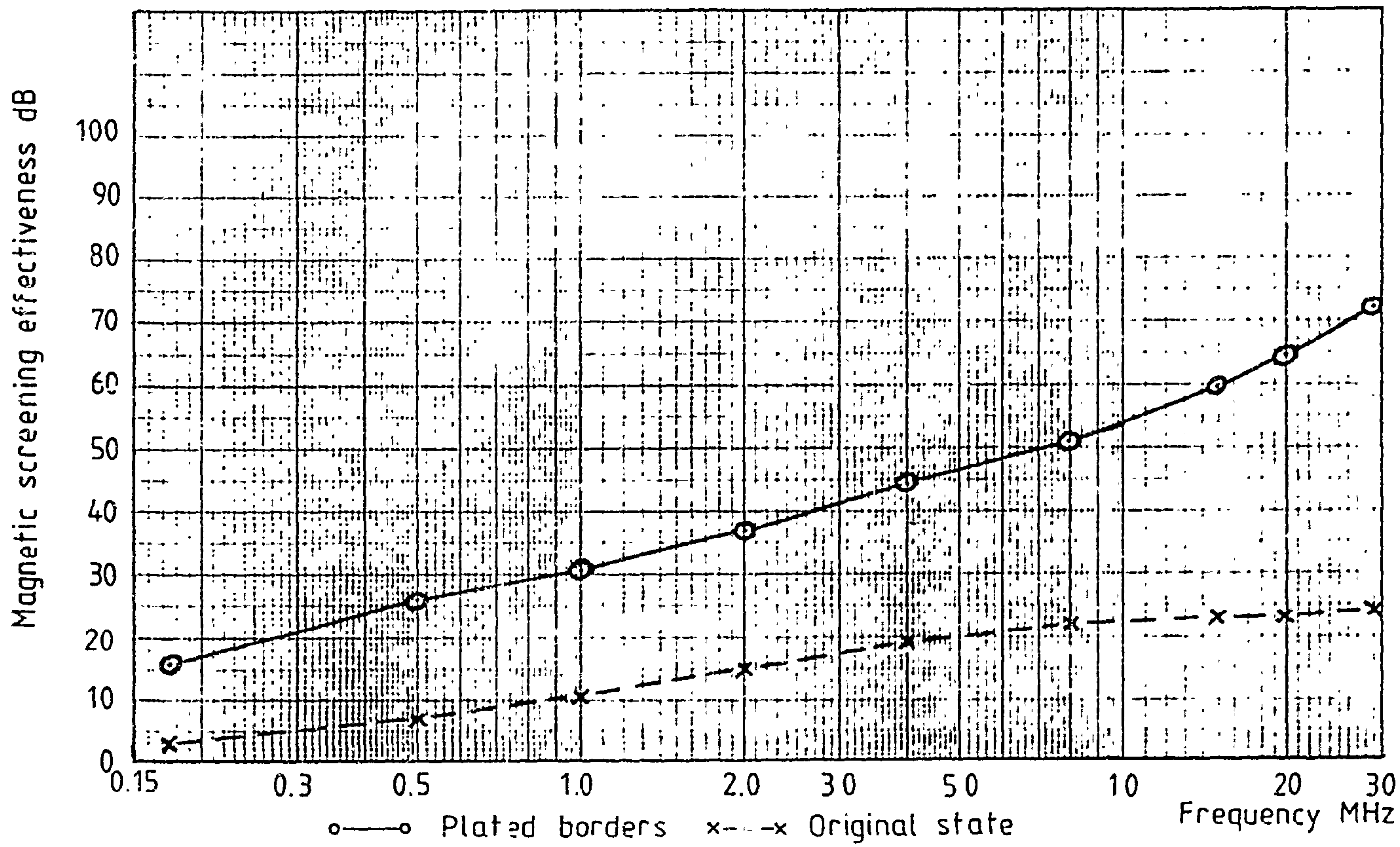


Figure 4 Magnetic screening effectiveness - sample P9(b)

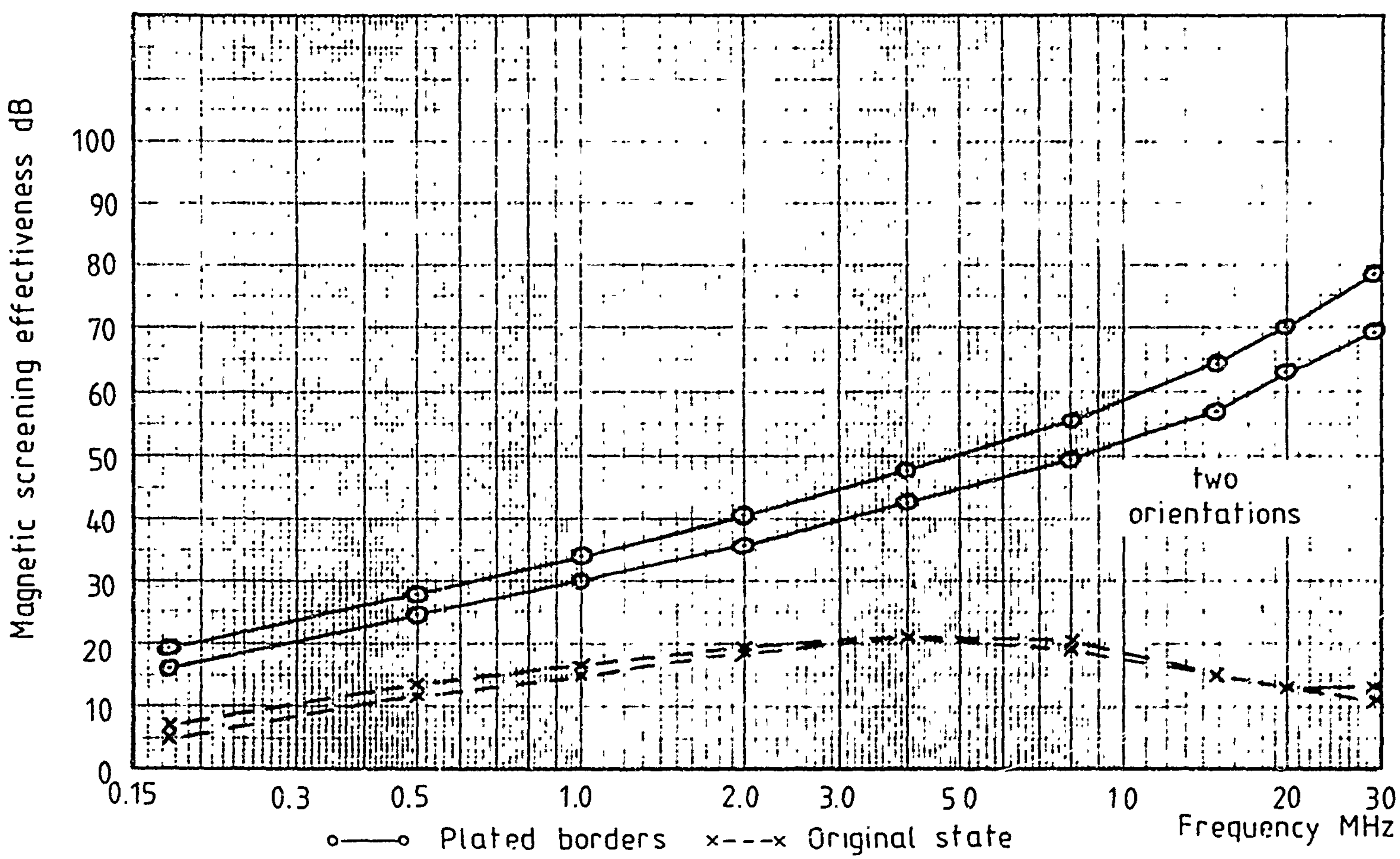


Figure 5 Magnetic screening effectiveness - sample P10

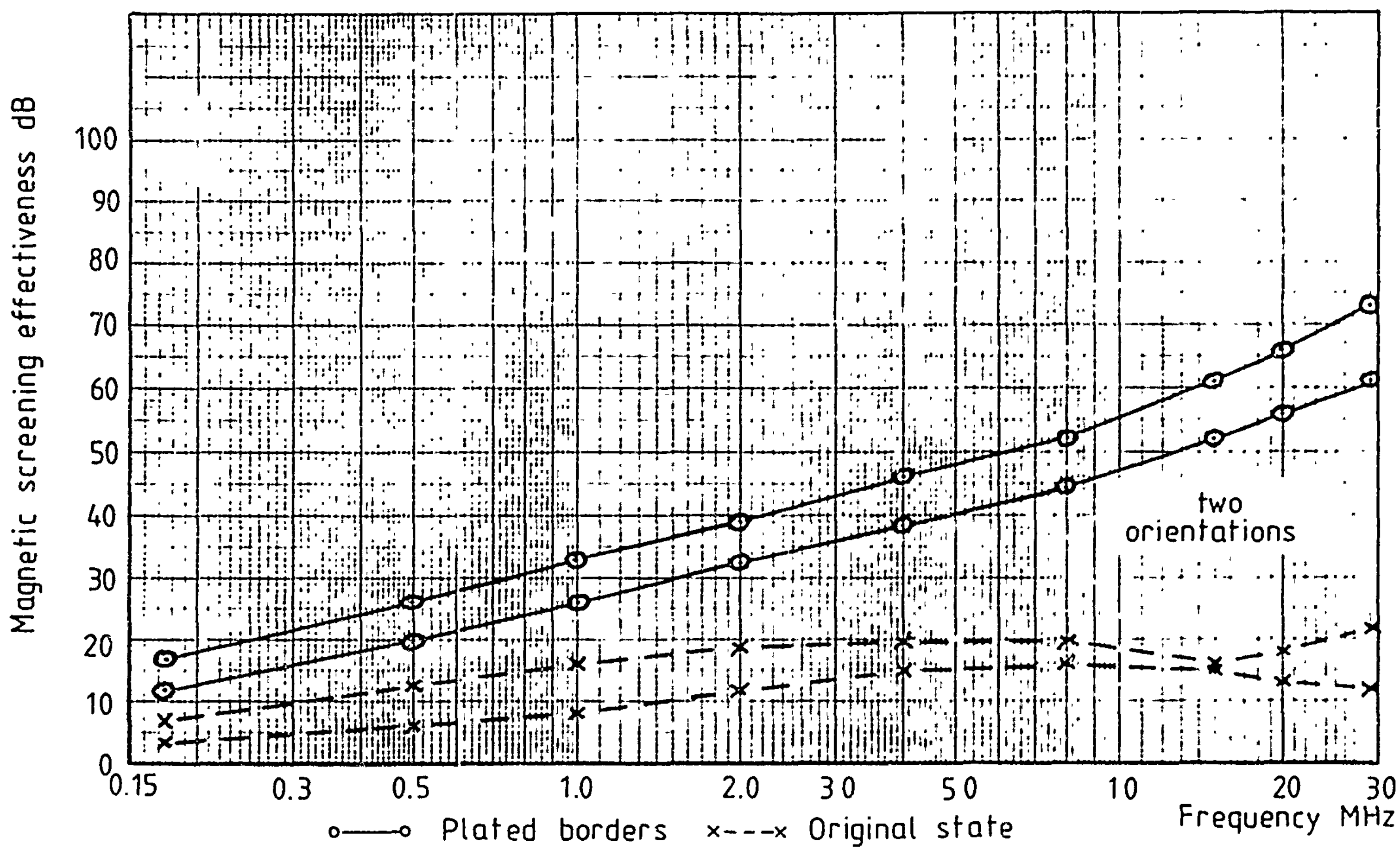


Figure 6 Magnetic screening effectiveness - sample P11

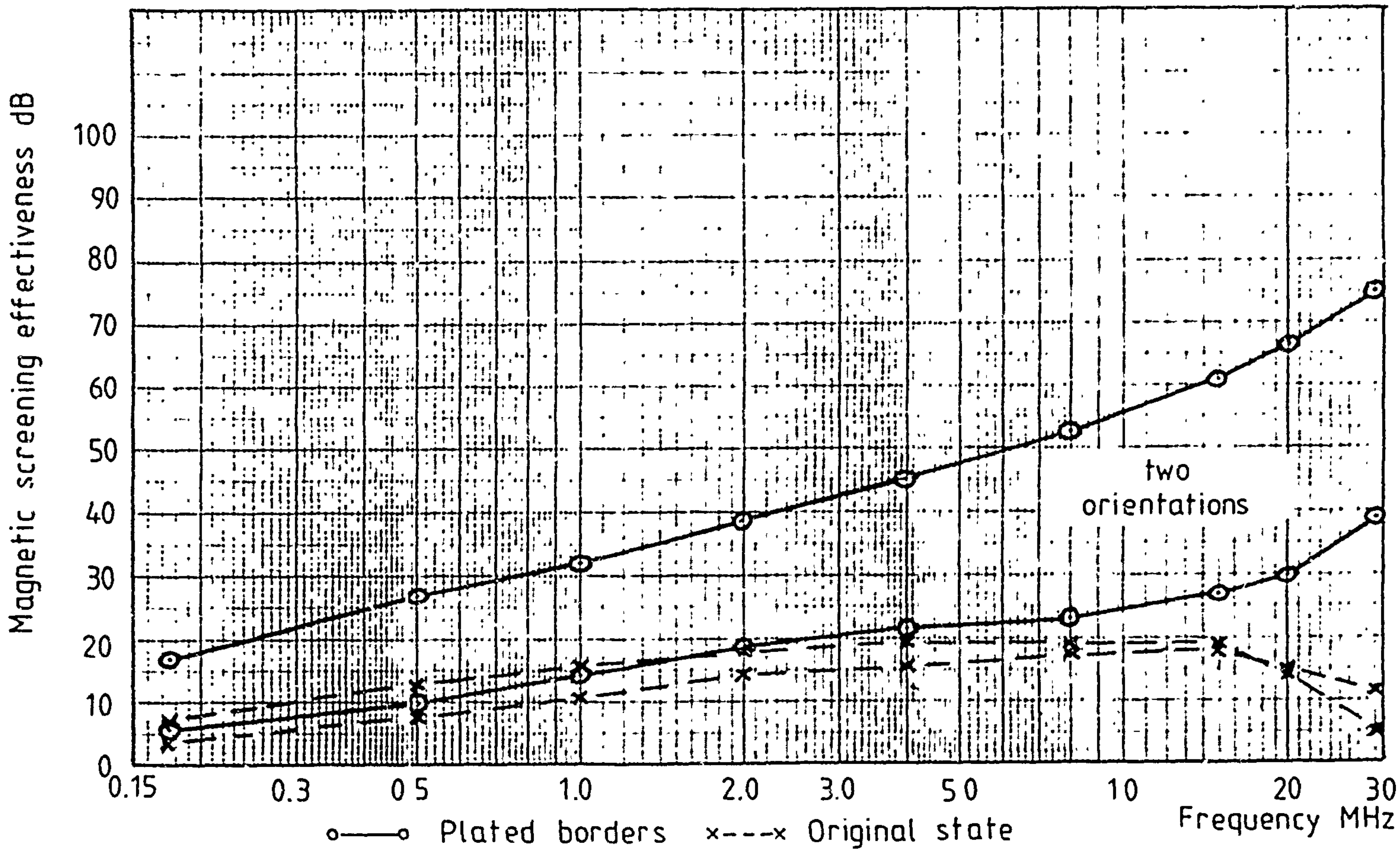


Figure 7 Magnetic screening effectiveness - sample P12

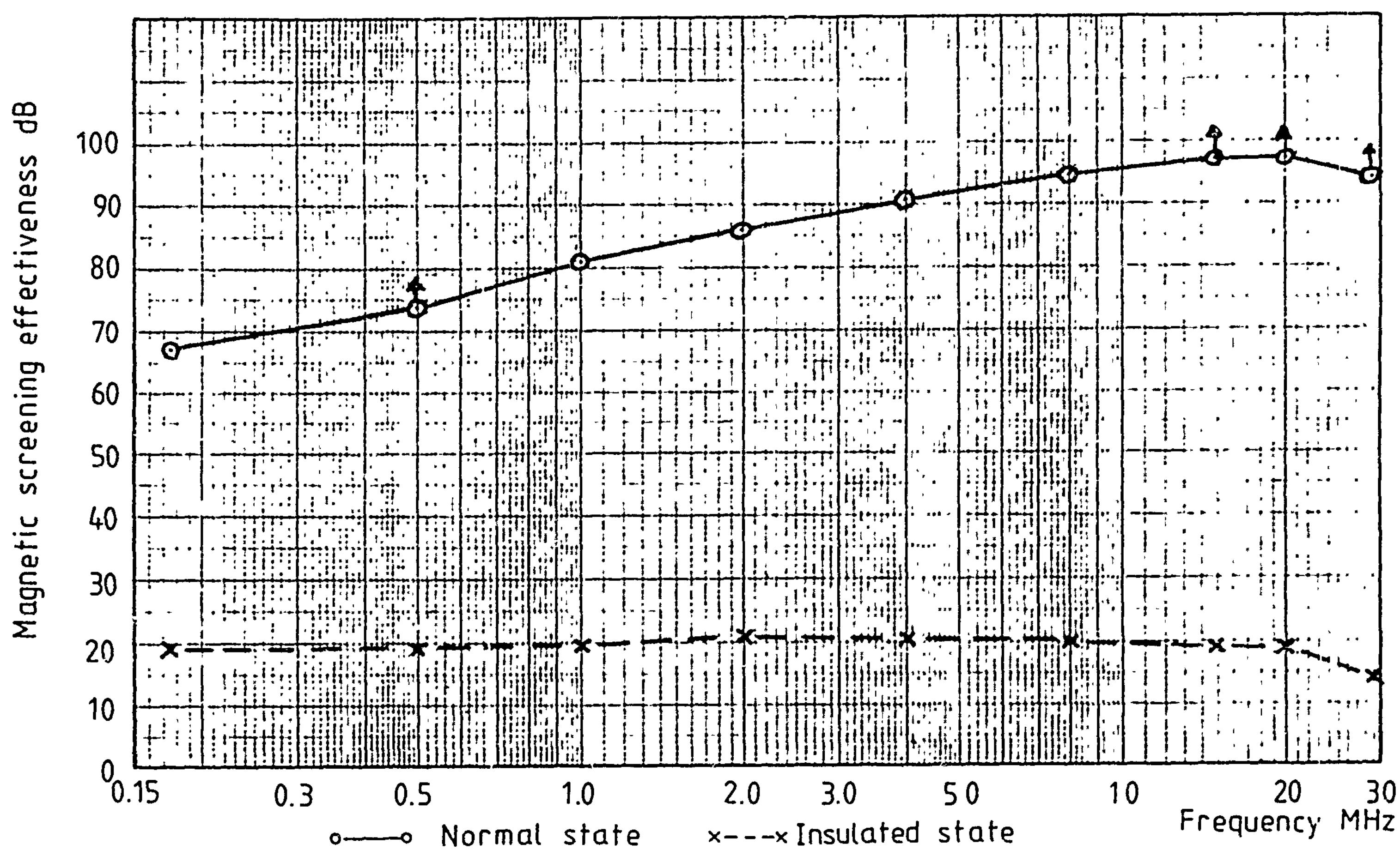


Figure 8 Magnetic screening effectiveness - 18 gauge aluminium

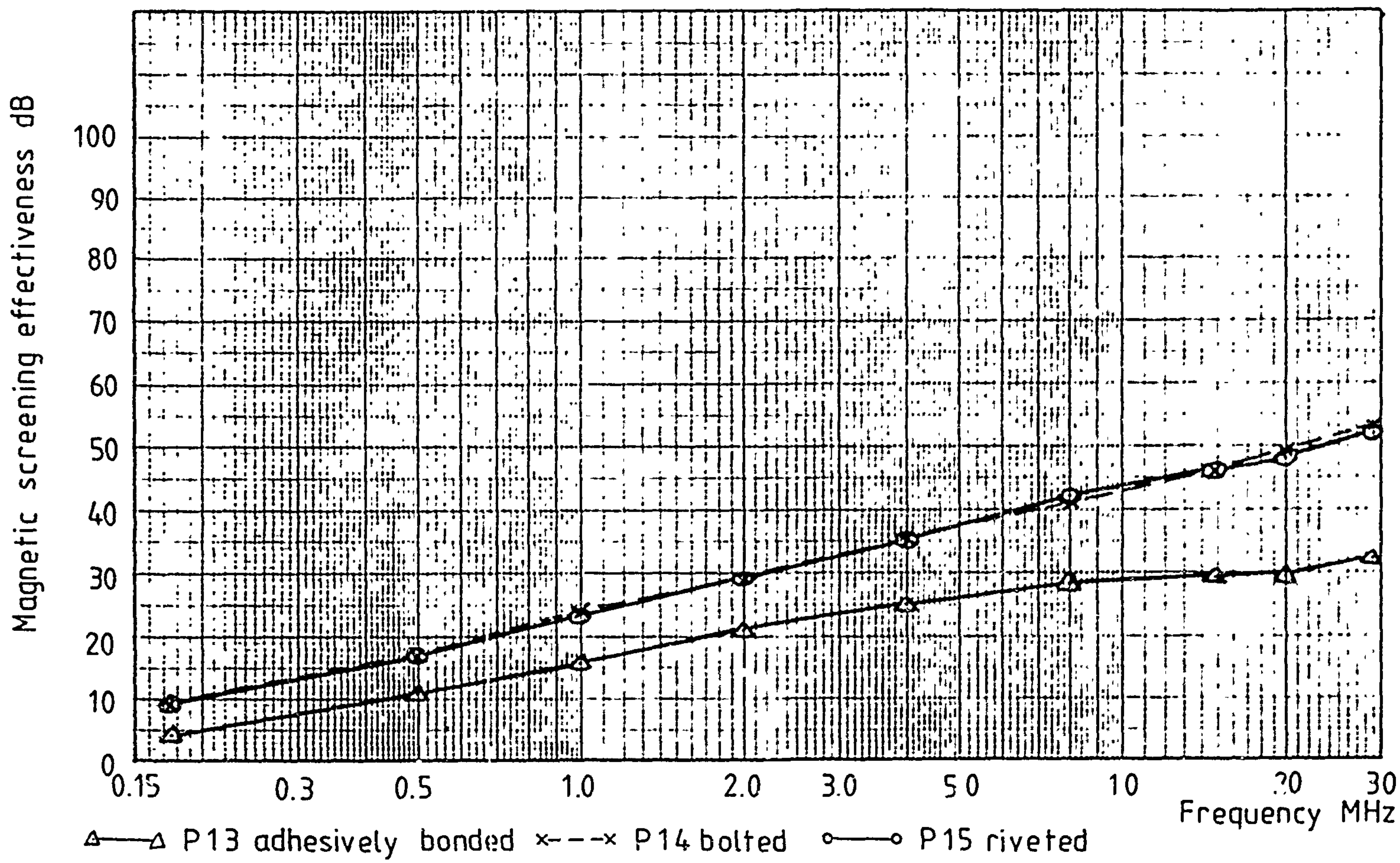


Figure 9 Magnetic screening effectiveness - sample P13, 14 & 15

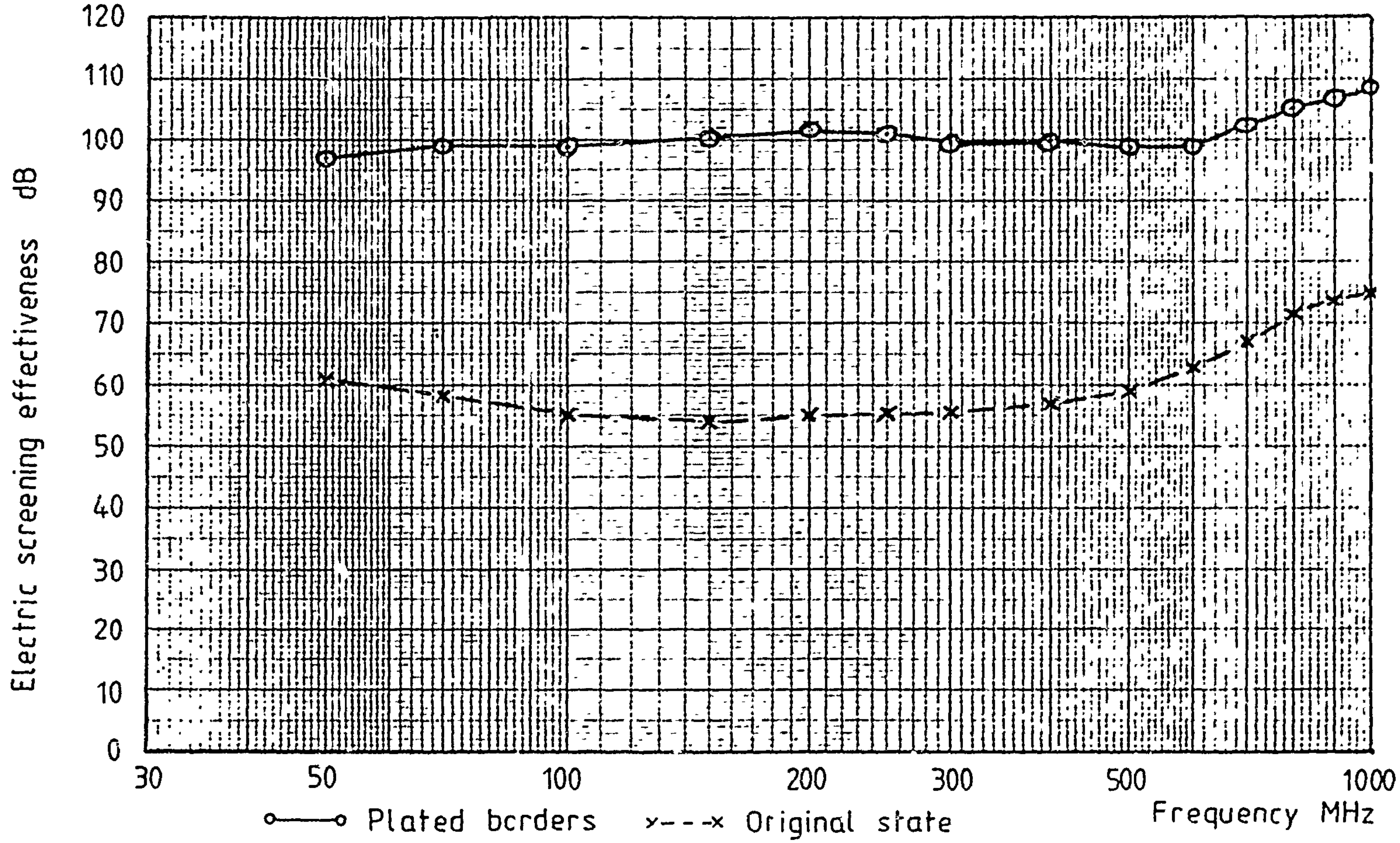


Figure 10 Electric screening effectiveness - sample P9(a)

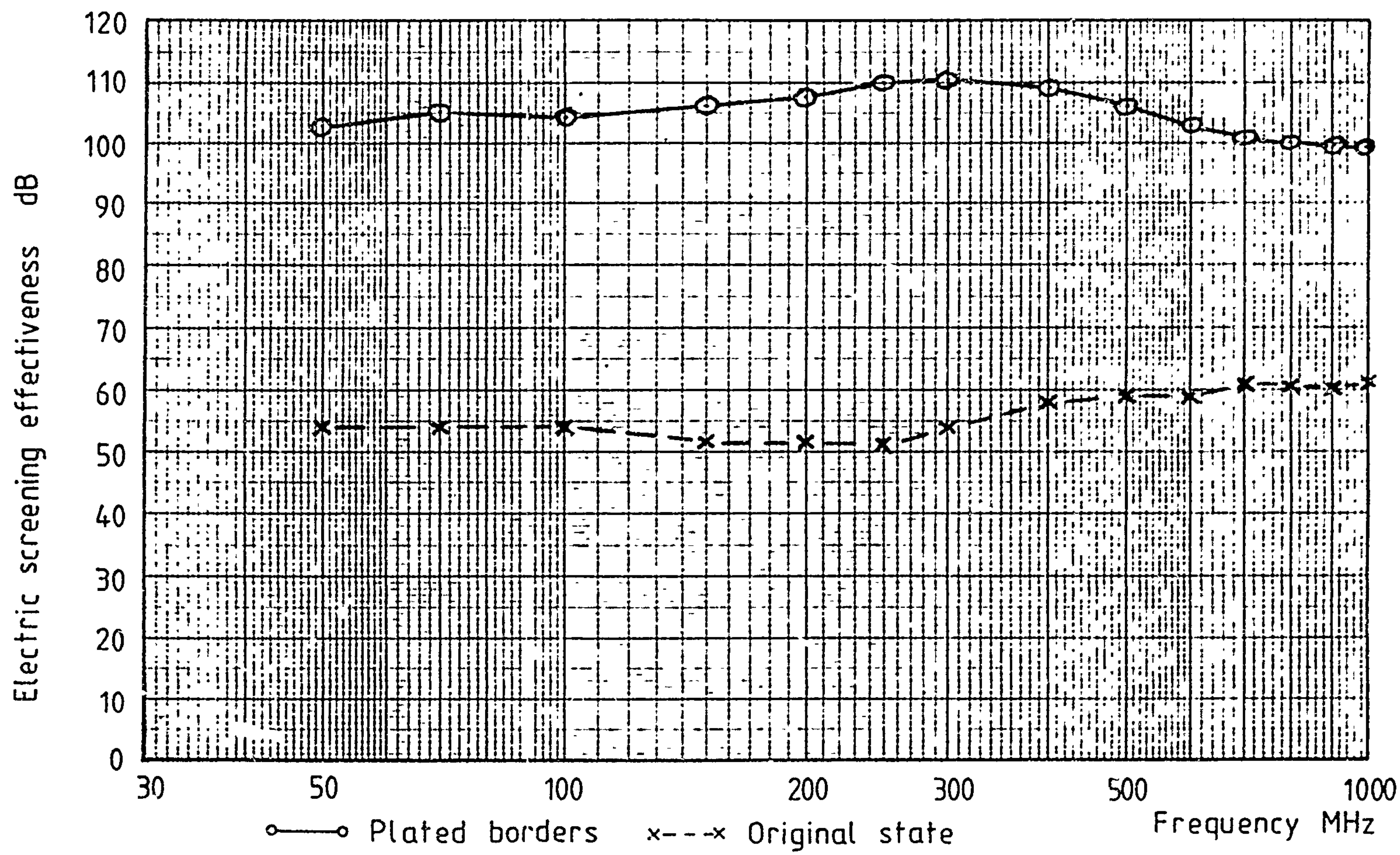


Figure 11 Electric screening effectiveness - sample P9(b)

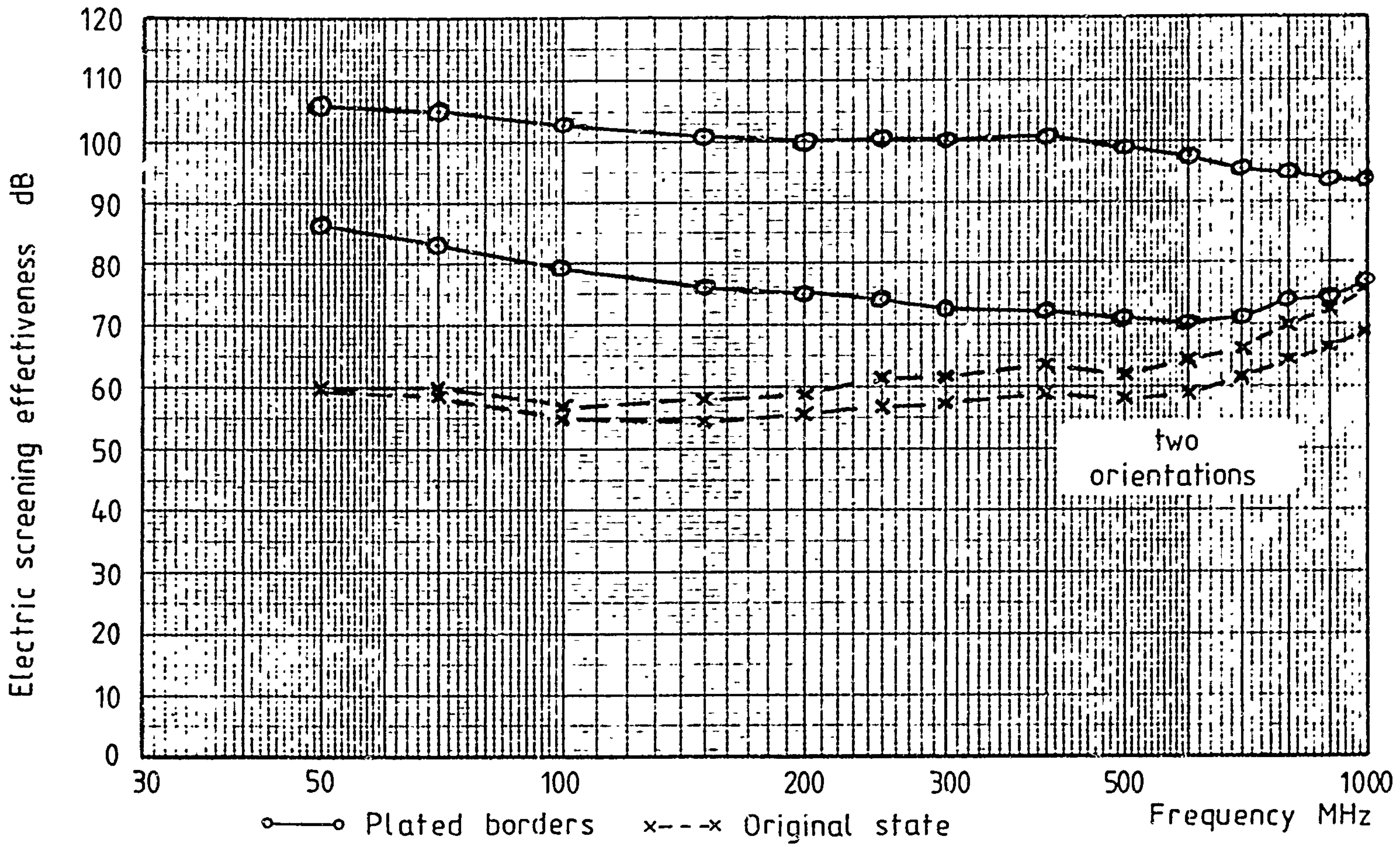


Figure 12 Electric screening effectiveness - sample P10

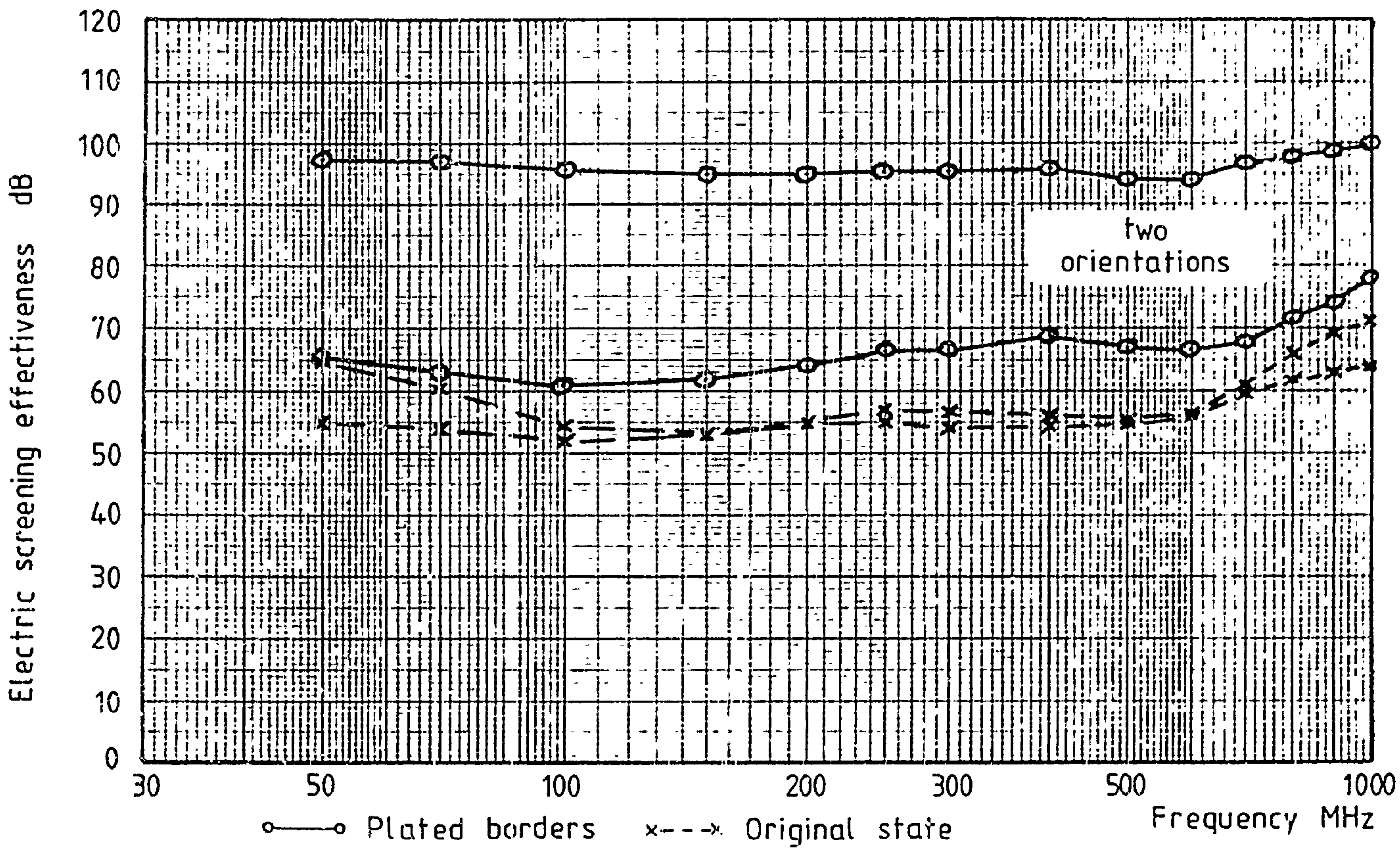


Figure 13 Electric screening effectiveness - sample P11

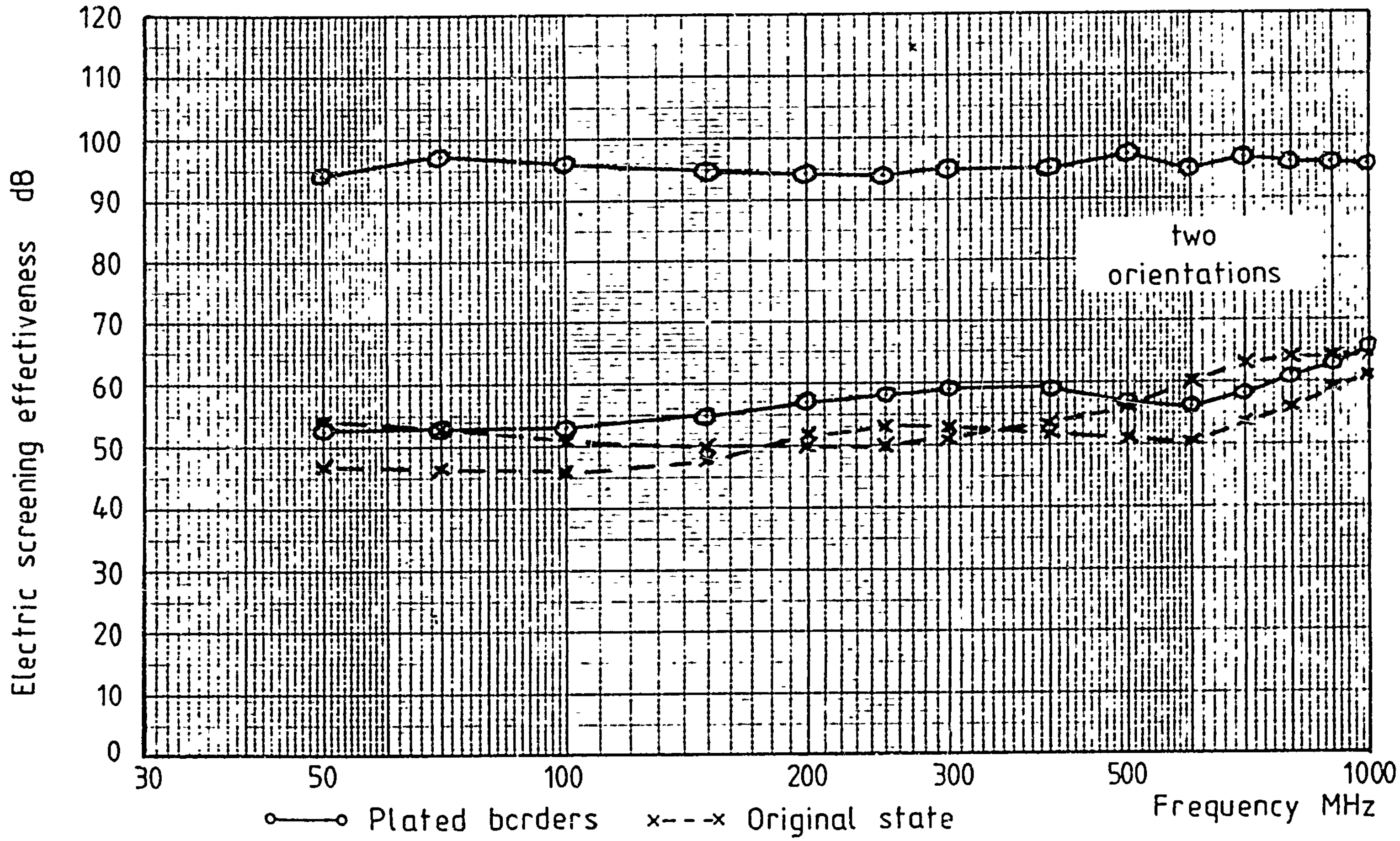


Figure 14 Electric screening effectiveness - sample P12

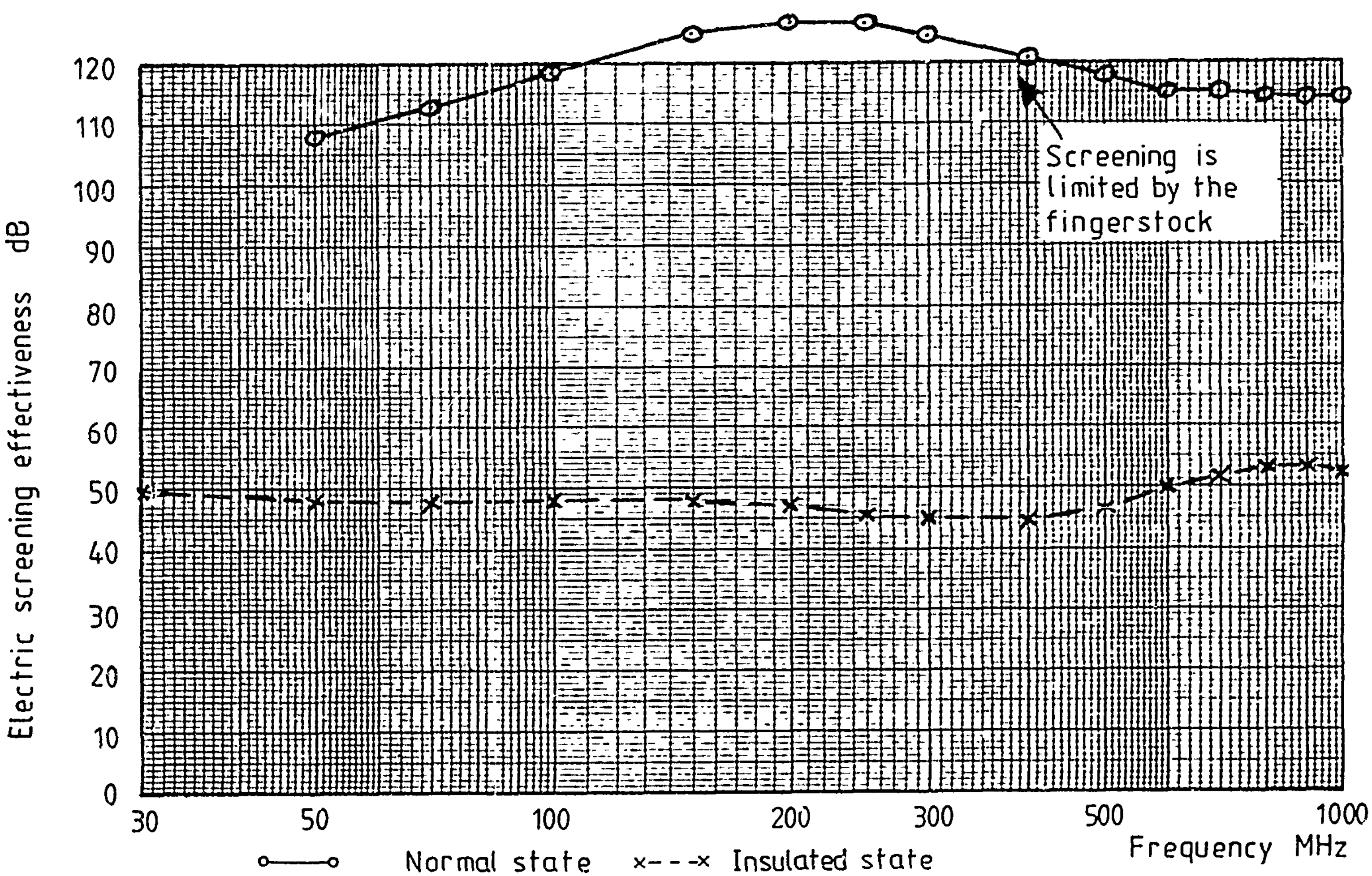


Figure 15 Electric screening effectiveness - 18 gauge aluminium

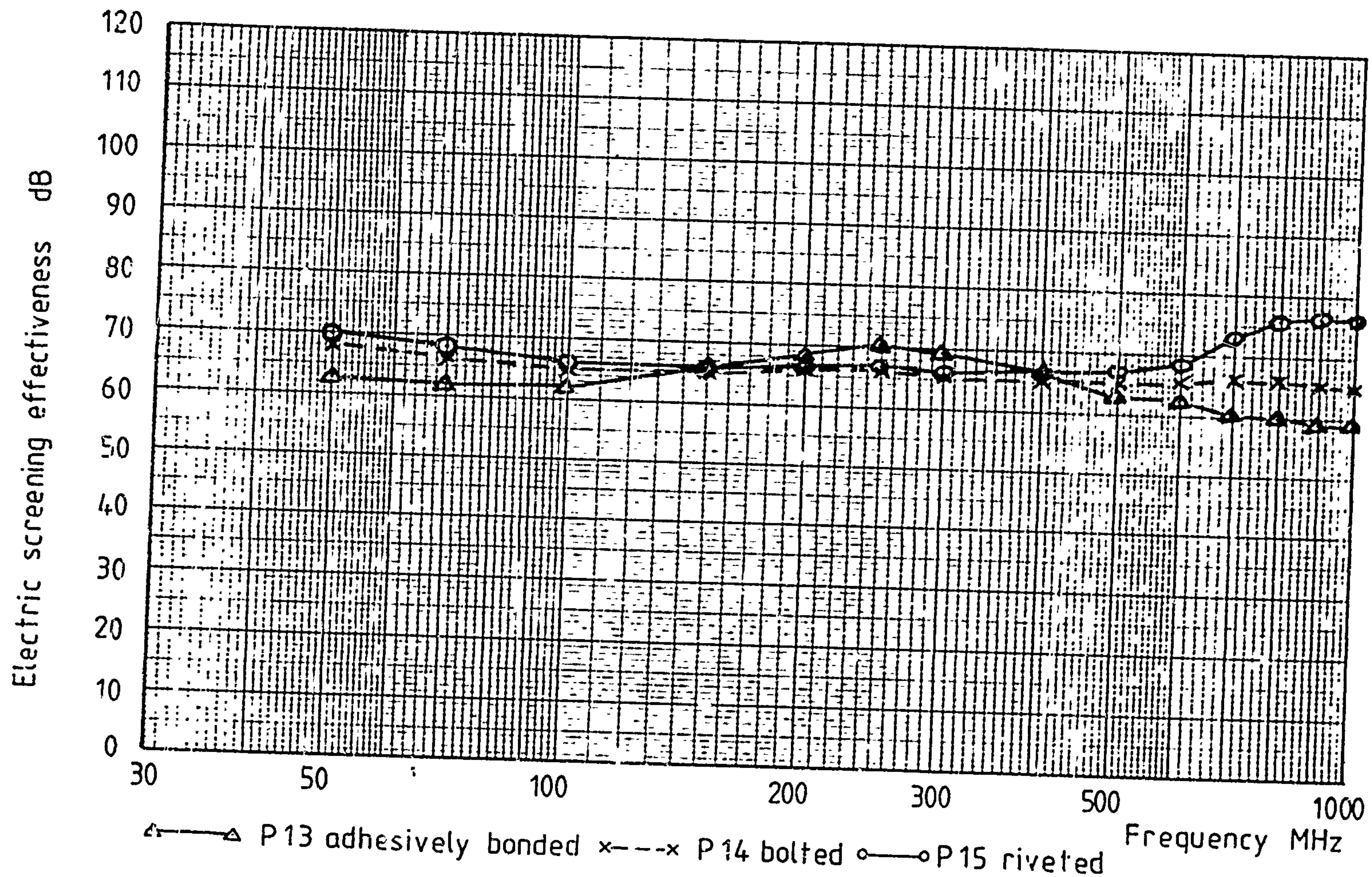


Figure 16 Electric screening effectiveness - sample P13, 14 & 15

APPENDIX A

SCREENING RESULTS AFTER LIGHTNING TESTS

The screening measurements were repeated for P2-P5 after these samples had undergone lightning tests at Culham Laboratory.

One significant change was found in the results for P4, the sample with the aluminium infill. There was little change to the magnetic results; however the electric screening effectiveness after lightning tests, shown in Fig.A1 for one orientation only, was increased by up to 15 dB. Examination of this sample showed that, whereas prior to the lightning tests the skins of the sample were insulated from each other, there was now d.c. continuity (<1 Ω) between the skins.

No significant changes in screening results for the other samples could be directly attributed to the lightning tests. The copper plated border on sample P2 was degraded and this reduced the 'E' field screening by some 10 dB, Fig.A2. The screening improved to exceed the pre-lightning test values when the sample was replated.

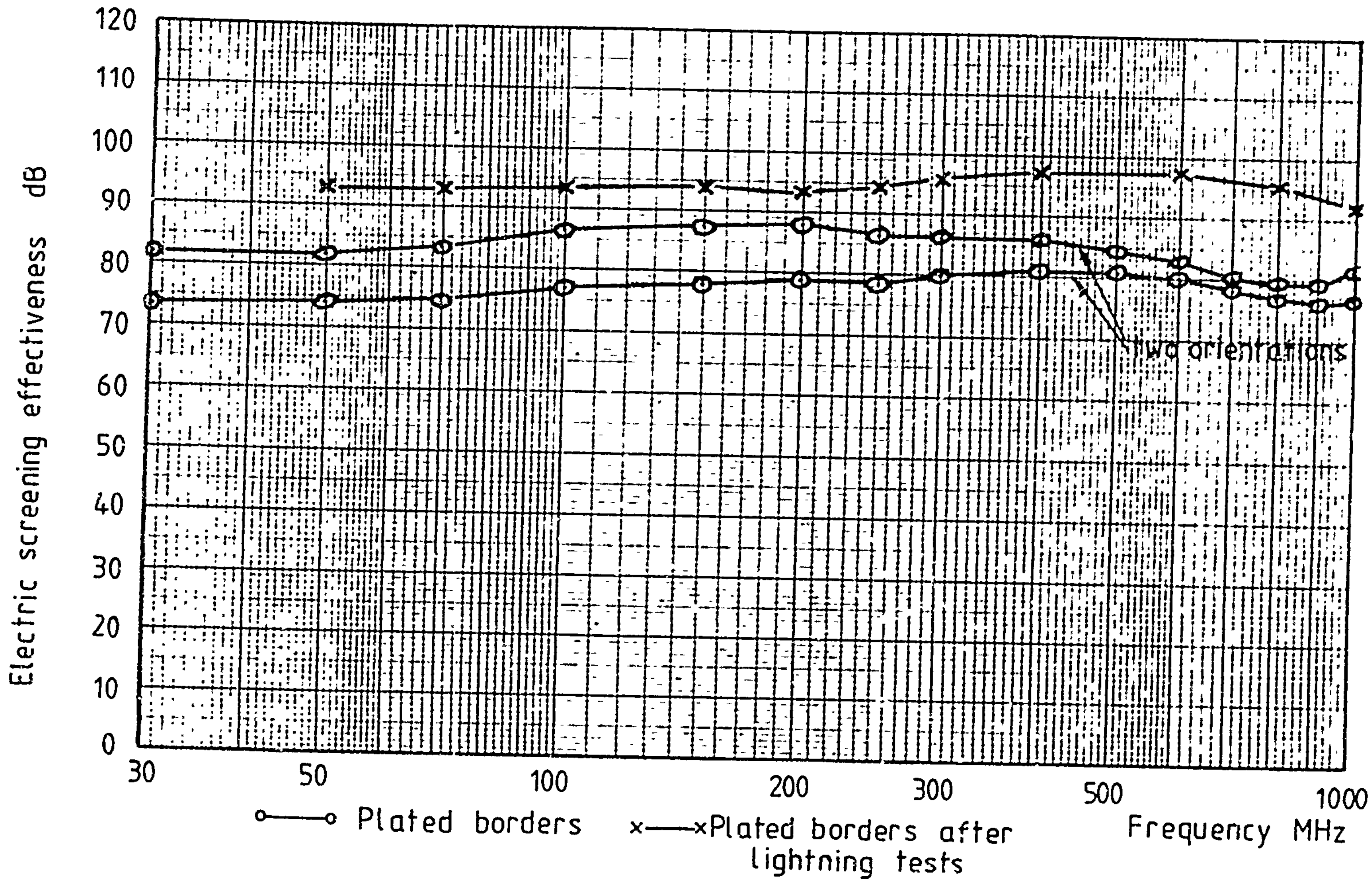


Figure A1 Electric screening effectiveness - sample P4

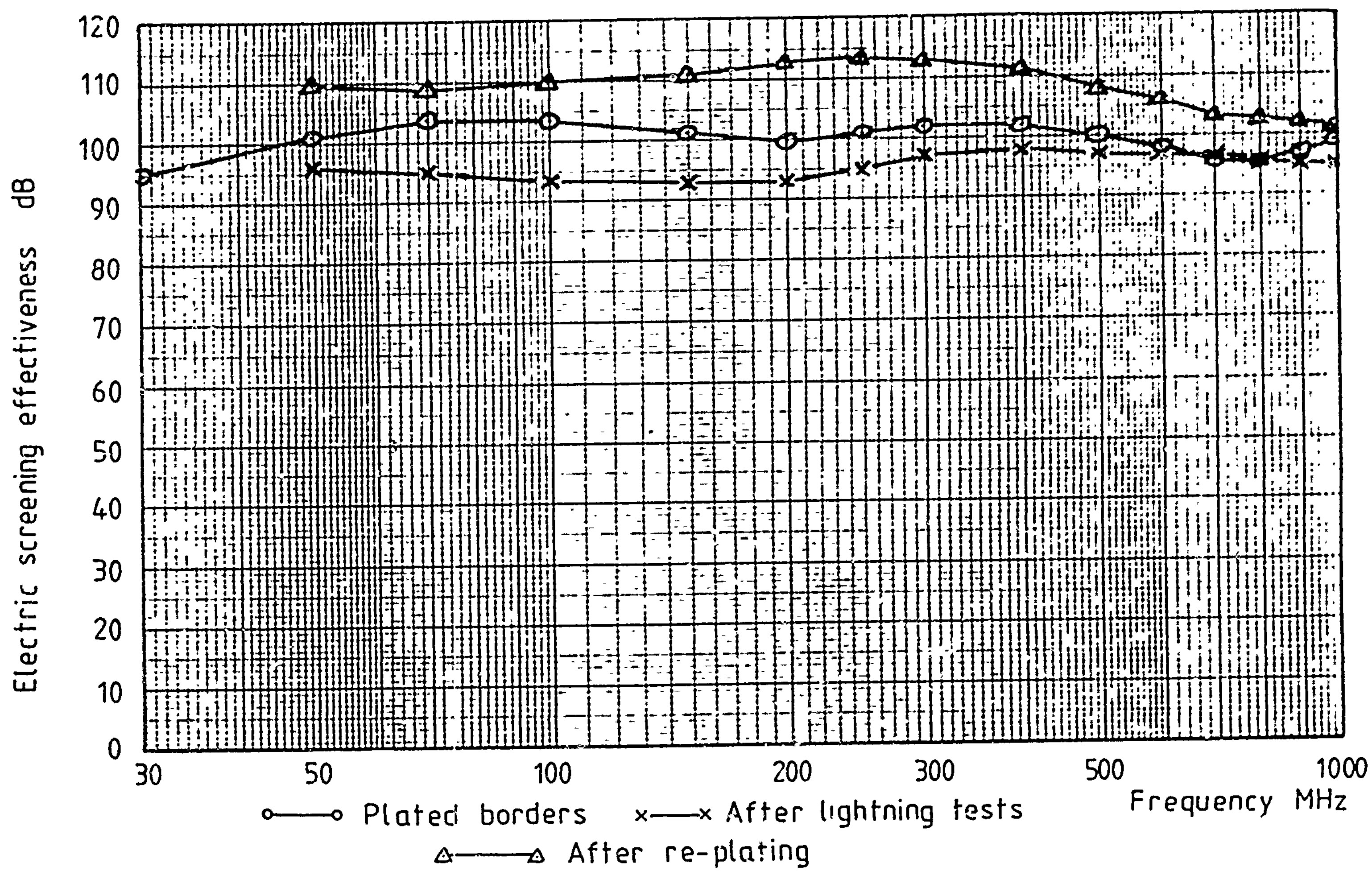


Figure A2 Electric screening effectiveness - sample P2

APPENDIX B

METHOD OF SMOOTHING THE ELECTRIC FIELD SCREENING RESULTS

The measured electric field screening characteristic for each CFC sample was found to fluctuate with frequency due to reflections within the enclosure. The degree of the fluctuation was reduced by damping the enclosure resonances by including resistive sheet material within the enclosure. However the residual fluctuations still impaired the comparison of the results for different samples. To facilitate comparison of various results, the following formula was developed to 'smooth' the curves by taking a weighted average of the values measured at adjacent frequencies.

Where S_n (dB) is the measured value at frequency f_n (MHz) the smoothed value S_s at frequency f_n is given by:

$$S_s = \frac{S_{n-2} \times \frac{f_{n-2}}{f_n} + S_{n-1} \times \frac{f_{n-1}}{f_n} + S_n + S_{n+1} \times \frac{f_n}{f_{n+1}} + S_{n+2} \times \frac{f_n}{f_{n+2}}}{\frac{f_{n-2}}{f_n} + \frac{f_{n-1}}{f_n} + 1 + \frac{f_n}{f_{n+1}} + \frac{f_n}{f_{n+2}}}$$

The frequencies used are those shown on the curves of results. At each end of the frequency range the end frequencies are repeated as necessary to complete the formula, viz:

for S_s at f_n = 1000 MHz and for S_s at f_n = 900 MHz

f_{n+1} and f_{n+2} were taken as 1000 MHz

and the measured screening value for 1000 MHz was used for S_{n+1} and S_{n+2}.

Figures B1 and B2 compare the 'raw' measured results for a jointed sample with the equivalent 'smoothed' results.

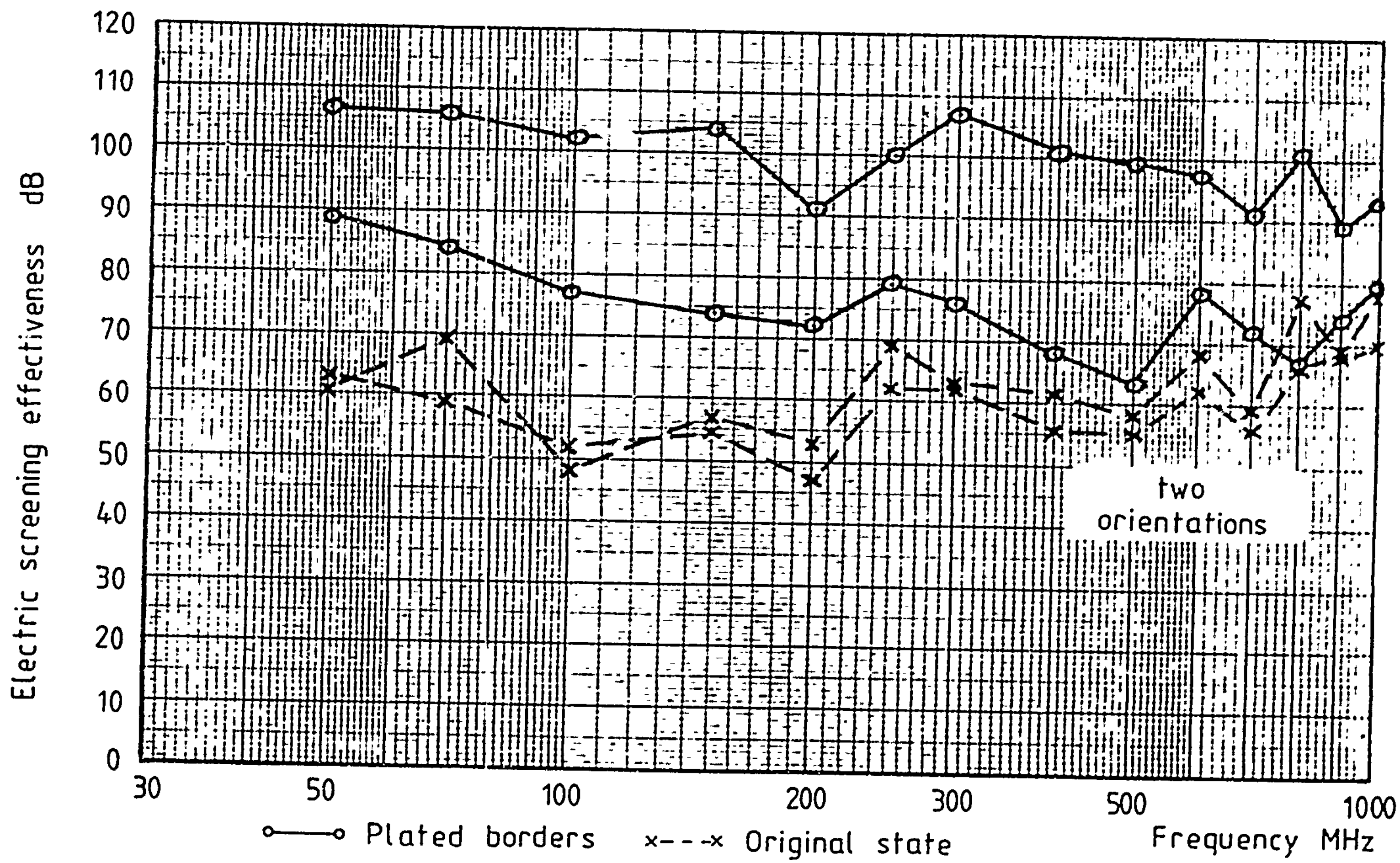


Figure B1 Electric screening effectiveness - sample P10 'raw' results

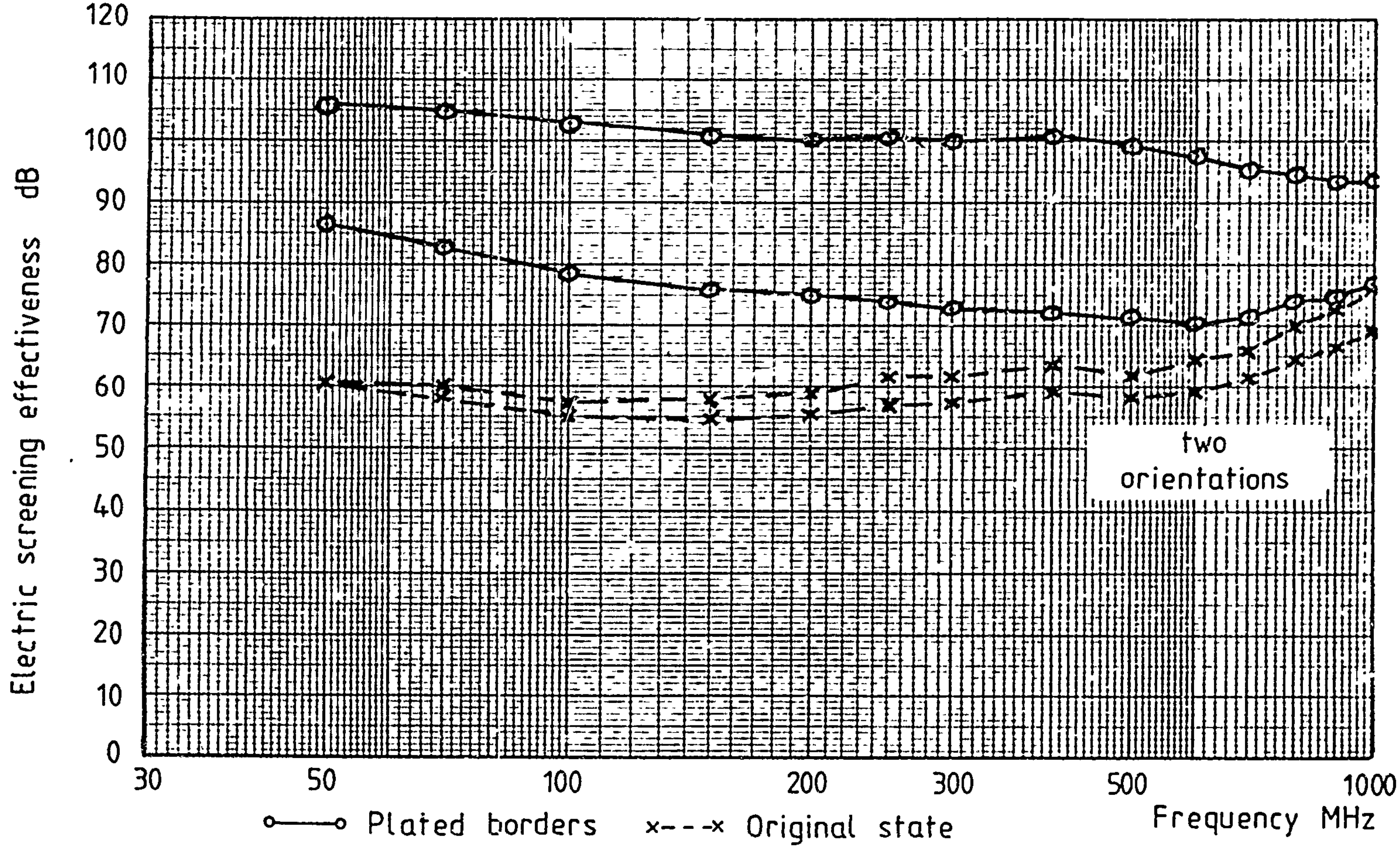


Figure B2 Electric screening effectiveness - sample P10 'smoothed' results

CHAPTER 5

FURTHER MEASUREMENTS OF THE SCREENING EFFECTIVENESS OF CARBON FIBRE COMPOSITE MATERIALS

A McHale

SUMMARY

Screening effectiveness to magnetic fields in the range 0.15-30 MHz and to electric fields in the range 30-1000 MHz has been measured for six further square CFC panels. The panel configurations investigated were under consideration by Westland Helicopters Limited for future helicopter designs.

Magnetic screening effectiveness rose linearly with increasing frequency reaching values, typically, of 50-60 dB at 30 MHz. Electric screening effectiveness was essentially constant, but rising slightly over the frequency range 30-1000 MHz; depending on the quality of the electrical contact at the edges of the sheets the values can range from approximately 50-90 dB.

The results show that screening integrity, particularly in the hf band, will be poor unless precautions are taken to achieve good electrical contact between panel sections or to the surrounding structure. In particular, the use of insulated 'bucket fasteners' and non-conductive adhesive to attach the panels to a metal (e.g. titanium) structure will give worse screening than would otherwise be expected from consideration of the characteristics of the CFC material alone.

CONTENTS

1 INTRODUCTION

In addition to the measurements of the screening effectiveness of various carbon fibre composite (CFC) panels reported in Chapter 4, ERA Technology Limited was tasked by MOD (PE) to test a further six 1 m^2 panels These panels were supplied by Westland Helicopters Limited (Yeovil) and represented a number of CFC configurations under consideration, early in 1981, for use in the construction of future rotating wing aircraft.

2 TEST PROCEDURE

The test procedures, definitions of screening effectiveness and the methods of presenting both magnetic and electric mode results are described fully in Chapter 4.

The test configurations for magnetic and electric mode measurements are also included, for reference, in Fig.1 of this Chapter. Details of the test panels are listed in Table 1. In addition Fig.2 shows the construction of test panel W6.

2.1 Test panels W1-W5

W1-W4 were tested in their original state and also after exposing and electroless copper plating the carbon fibres along the borders of one face to enable good electrical contact to be made to the copper enclosure. W5 was considered to be electrically very similar to W4 and so was only tested in its original state.

2.2 Test panel W6

W6 was not plated as this would have rendered the panel no longer typical of that proposed for the 'Advanced Technology Fuselage'. This panel was originally mounted by bolting through the panel's bucket fasteners to the brass rim around the enclosure aperture. This method of fixing, however, resulted in there being negligible electrical continuity between the panel and the enclosure.

In an airframe configuration, the poor electrical continuity between a panel and its supporting structure is likely to degrade the screening integrity unless good electrical joints are maintained between adjacent

CFC panels. It is expected, therefore, that some form of electrical continuity will be provided between the panels, perhaps by the use of a conductive sealant along the inter-panel joints.

Conducting joints were simulated for the magnetic mode screening measurements in this investigation by attaching copper foil to the two opposite panel edges which contain the aluminium sprayed 'Nomex' core and the bucket fasteners. Each foil strip, 1 m long x 0.05 m wide, was attached with self-tapping screws which were fastened at approximately 80 mm intervals along the filled edge of the panel. The rest of the width of the copper foil was folded onto the face of the panel to make contact with the enclosure. The edge of the carbon fibre faces was initially masked to prevent direct contact to the exposed fibre ends. This ensured that the only electrical contact between the panel and the enclosure was through the aluminium sprayed 'Nomex' core (i.e. where the screws compressed the foil against the core) and also to some extent between the core and the foil via the screws. The resulting joint impedance, measured at d.c. using a Kelvin bridge, averaged 5 Ω for the 1 m length.

After measuring the screening integrity of the panel in this condition, the tape which masked the fibre edges was removed and the test repeated. In this case the joint impedance at d.c. was reduced to 0.2 Ω by partial contact between fibre ends and the foil.

3 RESULTS

The screening results are presented graphically in Figs.3-7 for the magnetic mode and Figs.8-13 for the electric mode measurements. Each panel was attached to the enclosure using each of the two possible orientations. Where the results show small differences in screening between those two orientations the results curves are labelled 'two orientations'.

3.1 Magnetic mode

3.1.1 Test panels W1-W5

In their original state these panels, with the exception of W3, offered a maximum of 20 dB screening. This was considerably increased, especially

at higher frequencies, after electroless plating. In this latter condition, the screening increased linearly and was approximately proportional to frequency.

Considerably greater screening was obtained for W3, Fig.5, when the aluminium foil clad surface was mounted against the enclosure. A seam in the aluminium foil also affected the screening. When the panel was oriented with this seam horizontal, i.e. such as to impede the flow of rf current induced in the foil by the applied field, the screening was some 20 dB lower than when the seam was vertical.

3.1.2 <u>Test panel W6</u>

Four curves are shown in Fig.7. The two 'original state' curves show the screening to be independent of panel orientation at the lower frequencies. Above about 8 MHz the screening is greater when the panel is oriented with the fasteners and the aluminium sprayed core sections positioned top and bottom. These probably provide a predominantly capacitive path for the current in the panel and hence enhance the screening at the higher frequencies.

The remaining curves in Fig.7 show results for the simulated conducting joints. In both cases there is little difference from the 'original state' results at the lower frequencies. At the higher frequencies the configuration with the lowest joint impedance gives the greatest screening.

W6 contains a similar CFC lay-up to W4 and so useful comparisons can be made between the results for these two panels, Figs.6 and 7. The plated W4 gives more screening than the best W6 test configuration by some 5 dB at 175 kHz rising to 18 dB at 30 MHz. The d.c. surface impedance for each 4 ply laminate for both W4 and W6 is, by calculation, approximately 0.05 Ω per square. The joint impedances of the plated W4 are expected to be significantly less than this surface impedance and hence the value of the surface impedance would largely determine the screening. For W6, however, the joint impedances are greater than the surface impedance and the screening is reduced accordingly.

3.2 Electric mode

Figures 8 to 13 show the electric mode results. Screening for panels in their original state is typically 50-60 dB and shows little dependence on panel type. The screening tends to increase at the higher frequencies. In the plated condition a further improvement of between 20 and 50 dB was obtained.

4 CONCLUSIONS

Since airborne hf transmitters tend to be of higher power than those at vhf and uhf and as magnetic field penetration tends to dominate at lower frequencies the screening integrity of a fuselage at hf is of great importance. Results included in this report show that the screening integrity in the hf band is likely to be poor unless precautions are taken to achieve satisfactory electrical contact between panel sections or to the supporting frame. In particular, the use of insulated 'bucket fasteners' and non-conductive adhesive to attach the panels to a metal (e.g. titanium) frame would be expected to give screening results worse than otherwise indicated by a consideration of the characteristics of the CFC material alone.

Electric screening results for the CFC panels indicate that the screening, for a CFC fuselage, excluding the effects of apertures, should exceed 50 dB at vhf and uhf, particularly if electrical contact has been made to the panel edges to increase the hf magnetic screening integrity.

Table 1

Identification of test panels

ERA designation	Panel markings	Configuration
W1	RCL 947	8 plies of $\pm 45^{\circ}$ BSL913/XAS carbon with BSL916/120 glass on one surface. Panel has balanced lay-up.
W2	-	As for W1 only with 'Thorstrand' aluminium coated glass fibre replacing the glass.
W3	RCL 948	As W1 but with 'Brochier' aluminium foil pre-preg replacing the glass.
W4	RCL 951	As W5 but with micro balloon filled araldite edges. Filler specification WGPS 207 Type 2.
W5	RCL 952	4 plies of $\pm 45^{\circ}$ BSL913/XAS on either side of 'Nomex' core A1/48/3 of approx.12 mm thickness. Outer surface on both sides BSL916/120 glass on surface. Carbon to core bond with BSL913 UL.
W6	-	A panel with edges typical of that proposed for the 'Advanced Technology Fuselage'. 4 plies of $\pm 45^{\circ}$ BSL913/XAS on either side of 'Nomex' core A1/48/3 of approx.12 mm thickness. Two opposite edges contain bucket fasteners and aluminium sprayed 'Nomex' core. See Fig.2.

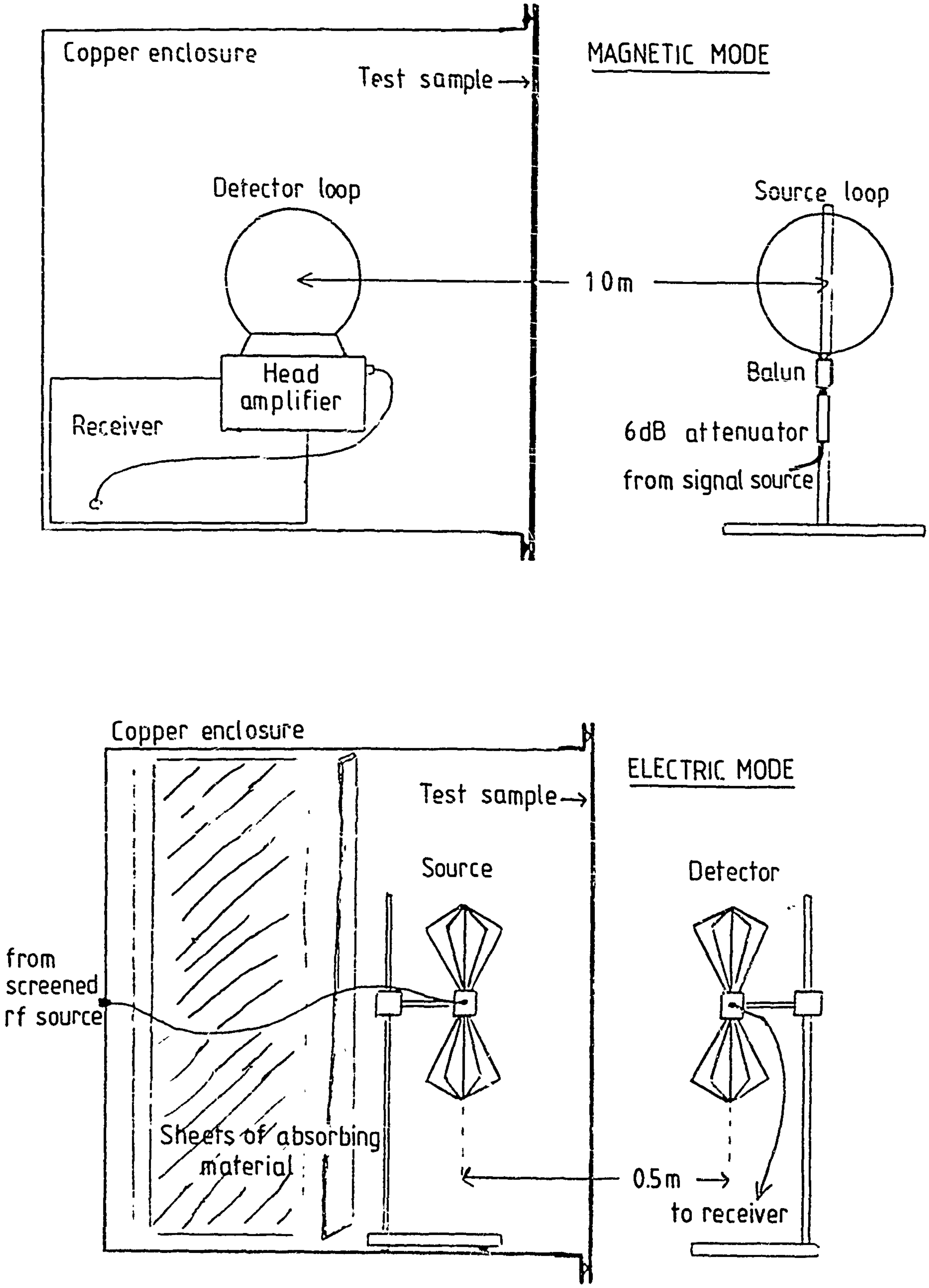


Figure 1 Test configurations for screening measurements

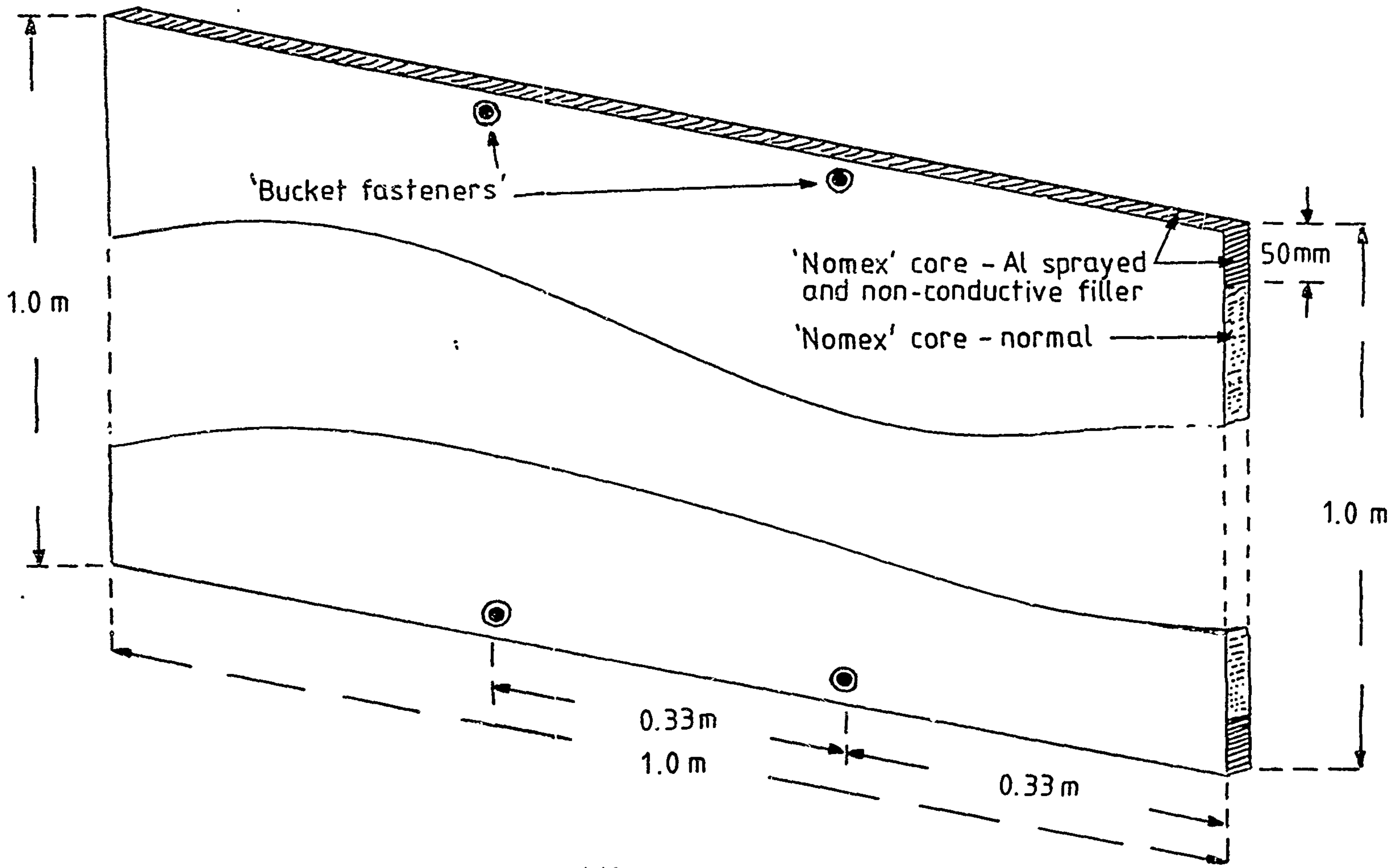


Figure 2 Construction of panel W6

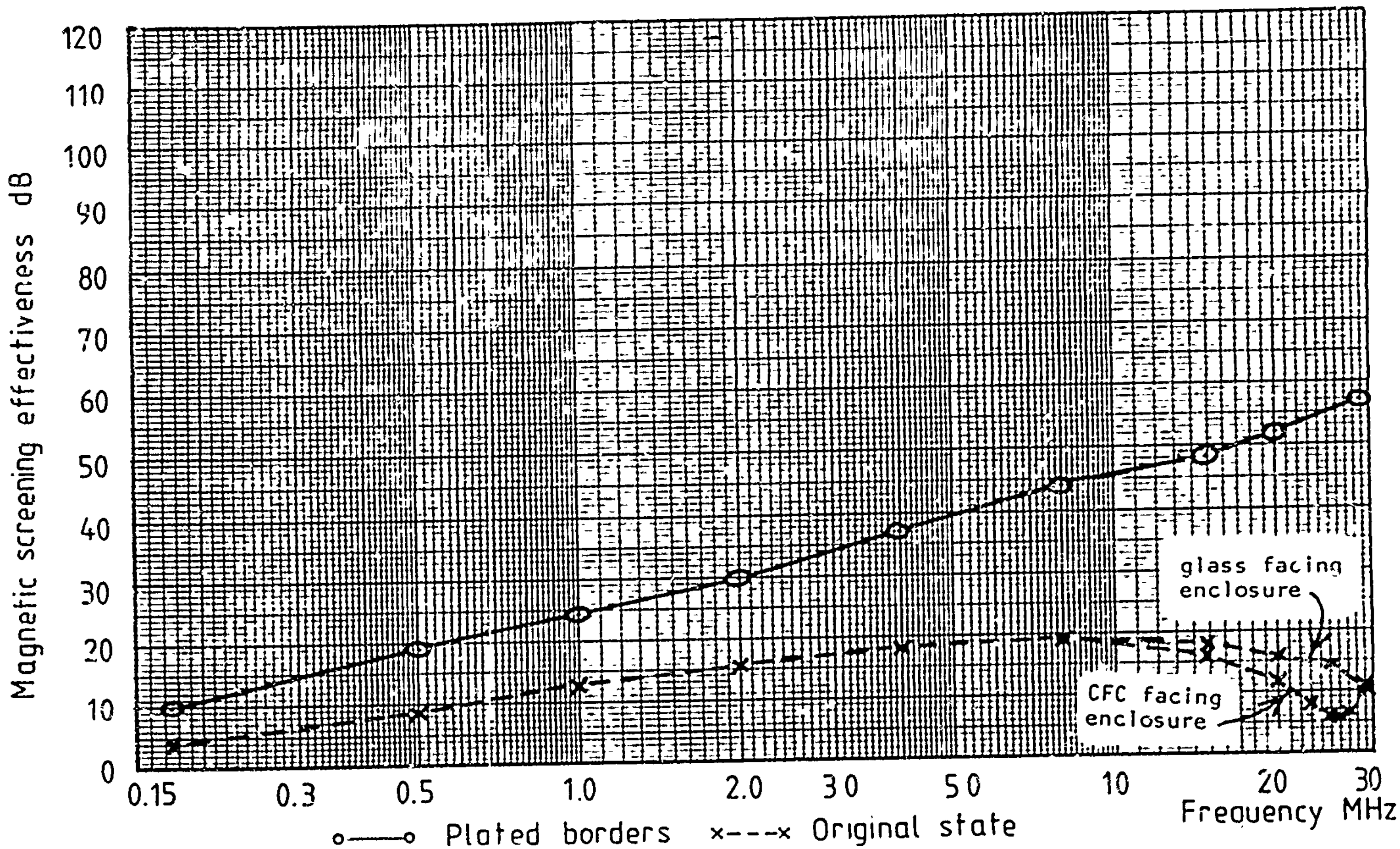


Figure 3 Magnetic screening effectiveness - panel W1

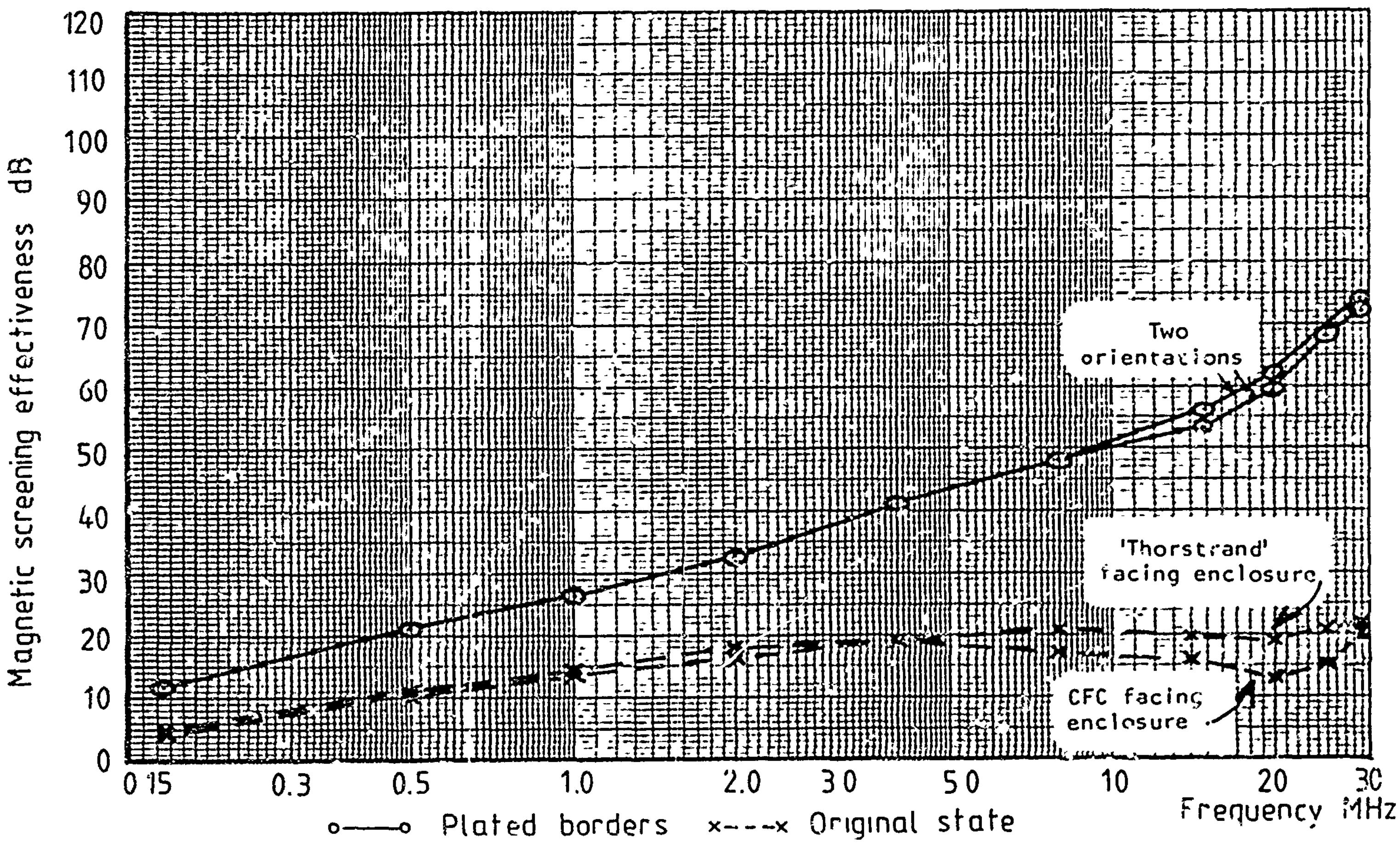


Figure 4 Magnetic screening effectiveness - panel W2

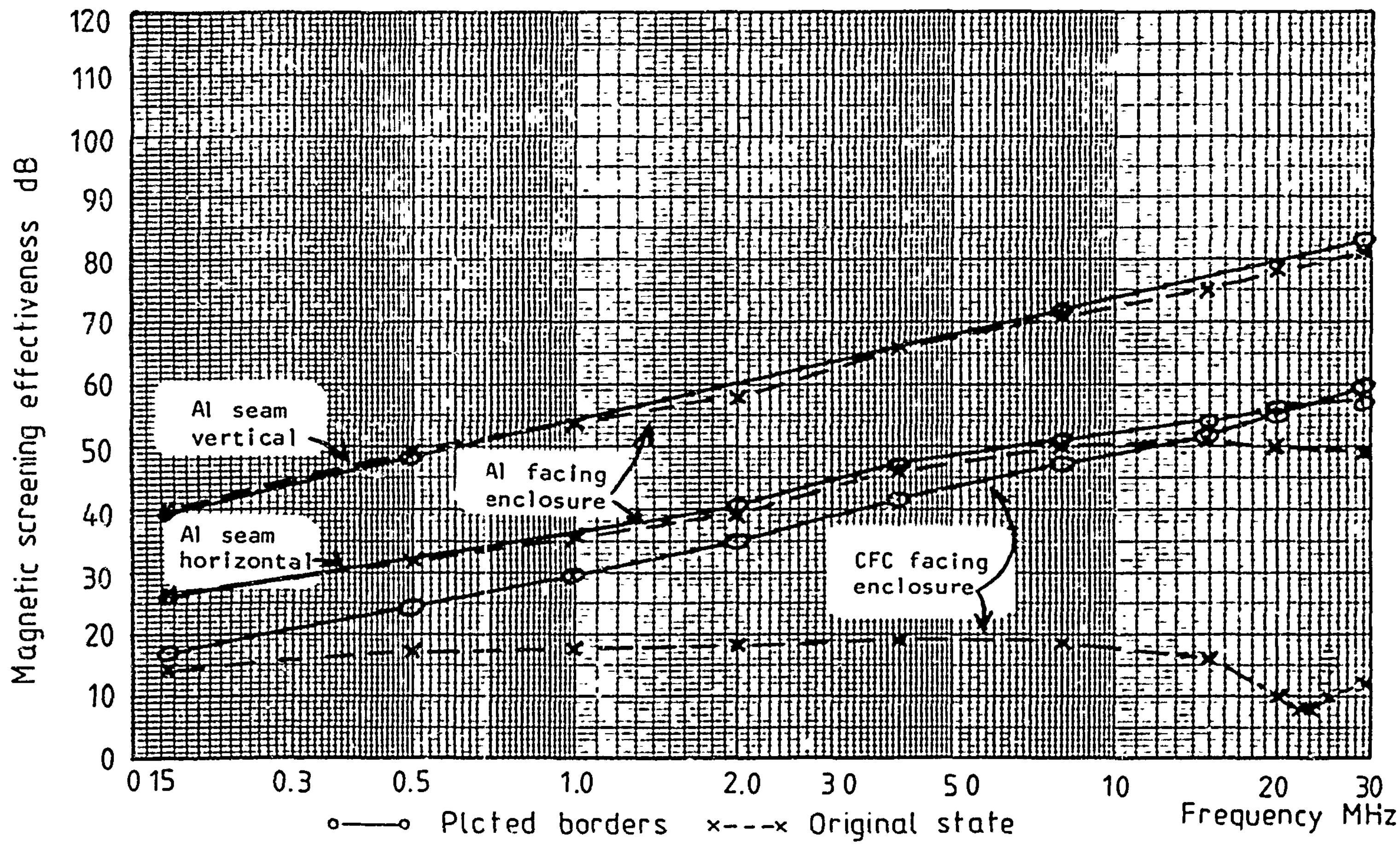


Figure 5 Magnetic screening effectiveness - panel W3

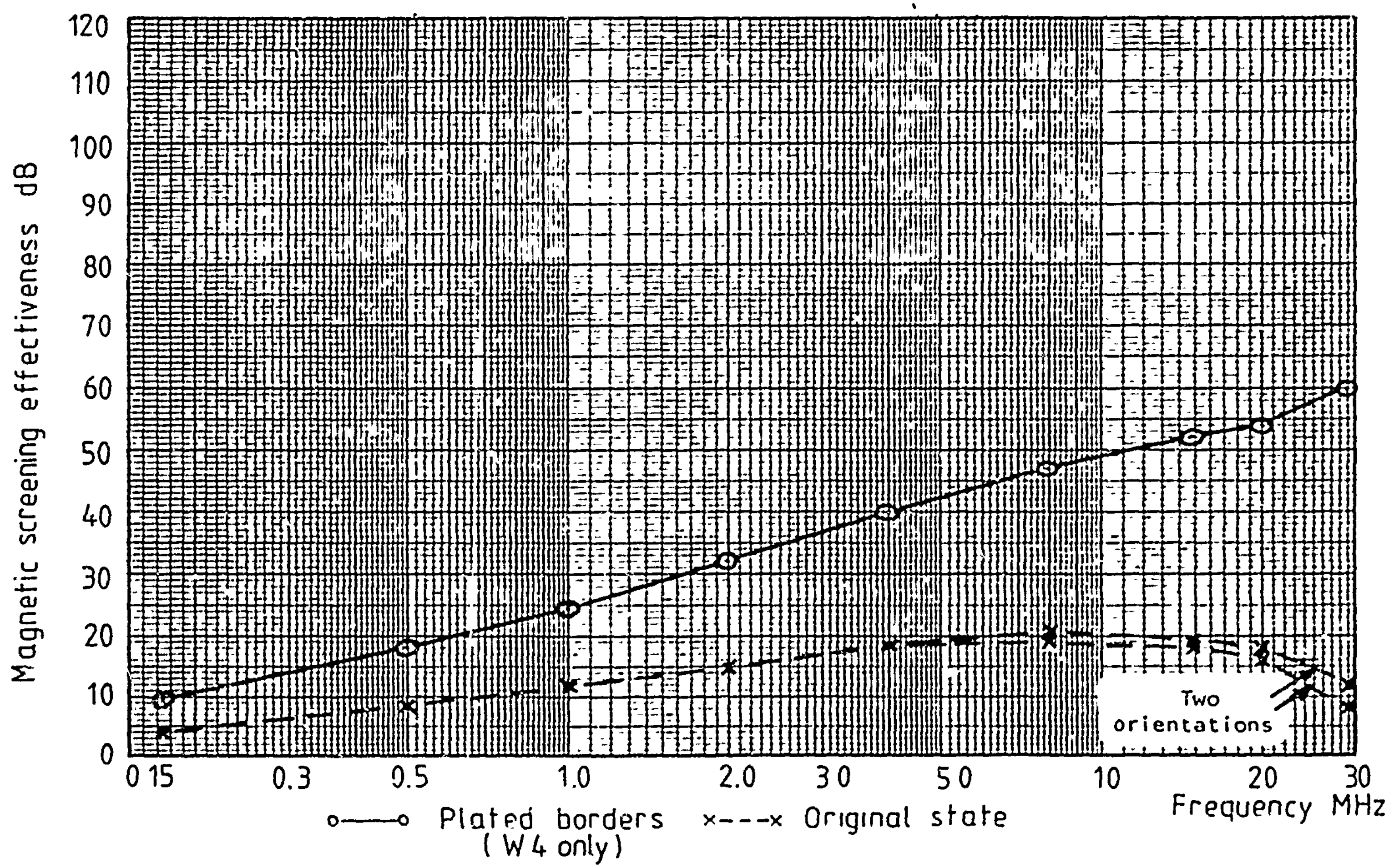


Figure 6 Magnetic screening effectiveness - panel W4 & W5

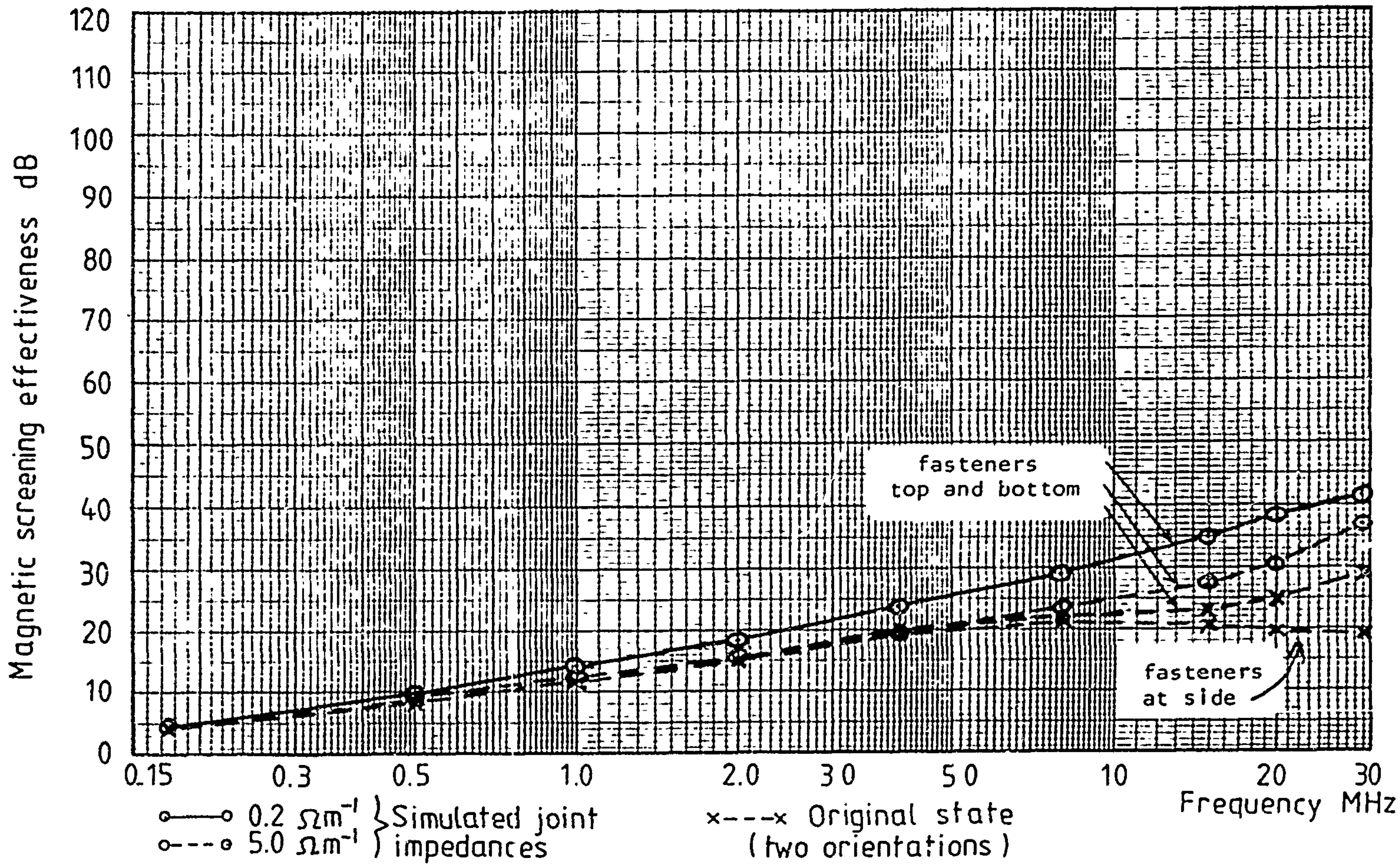


Figure 7 Magnetic screening effectiveness - panel W6

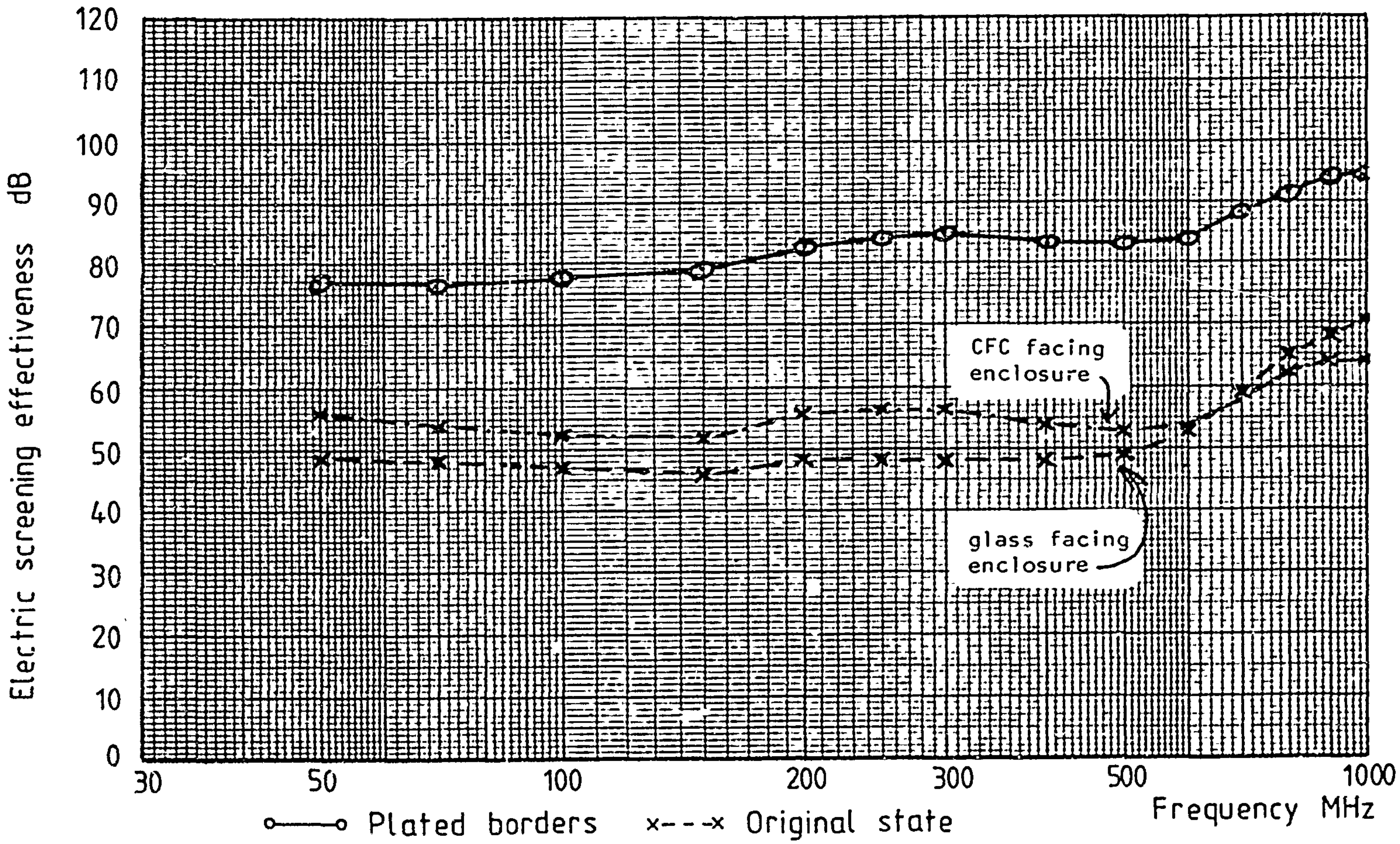


Figure 8 Electric screening effectiveness - panel W1

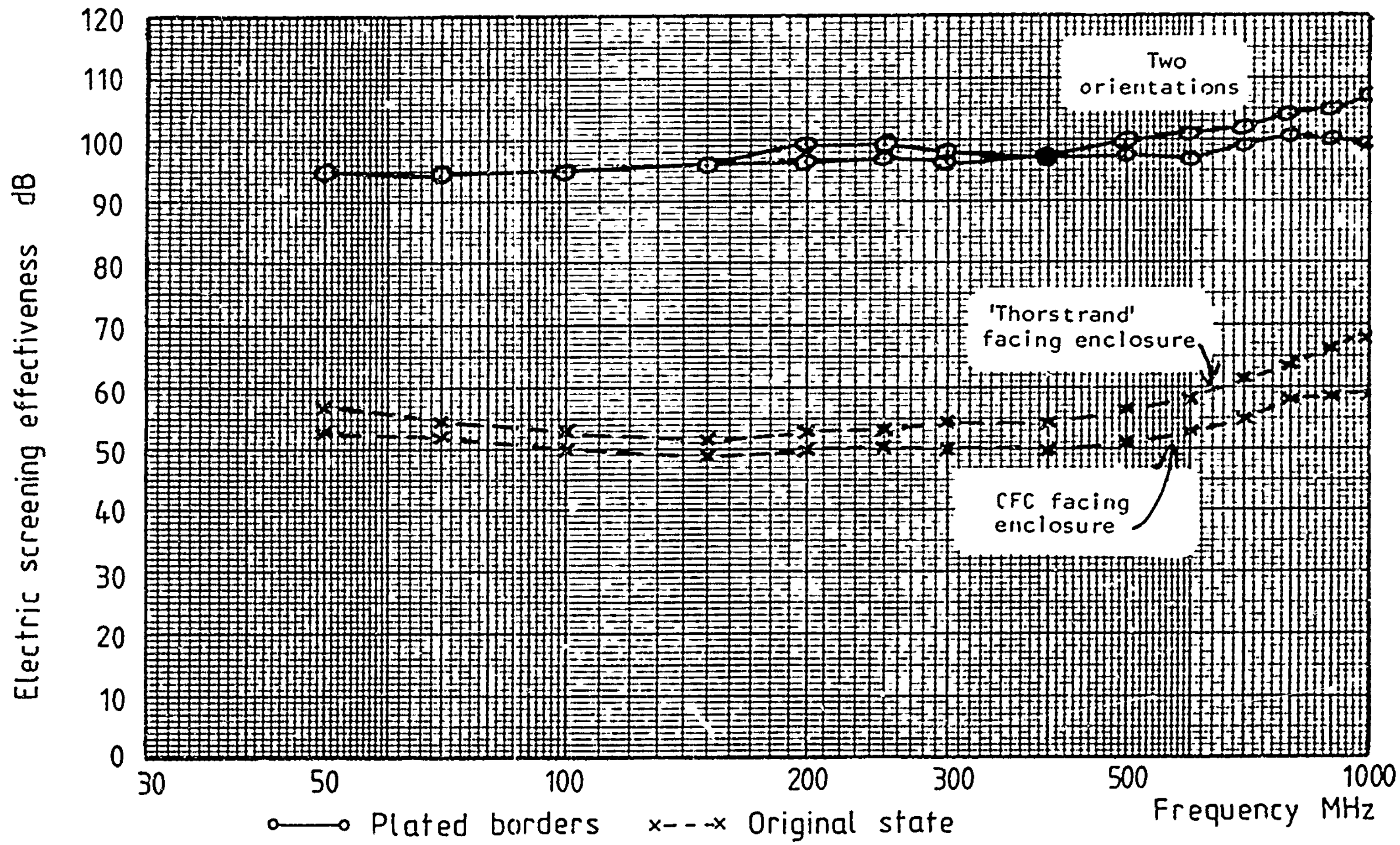


Figure 9 Electric screening effectiveness - panel W2

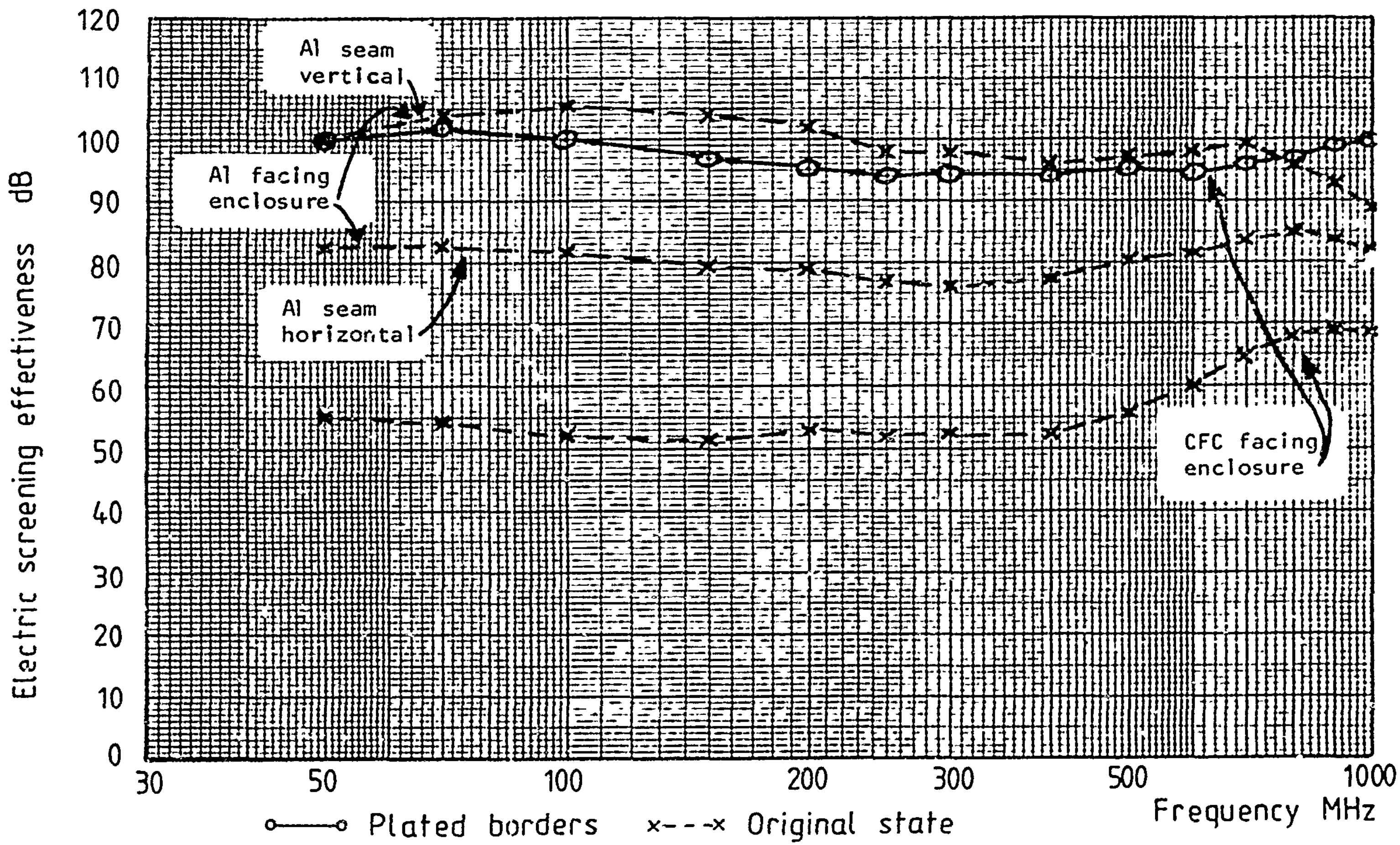


Figure 10 Electric screening effectiveness - panel W3

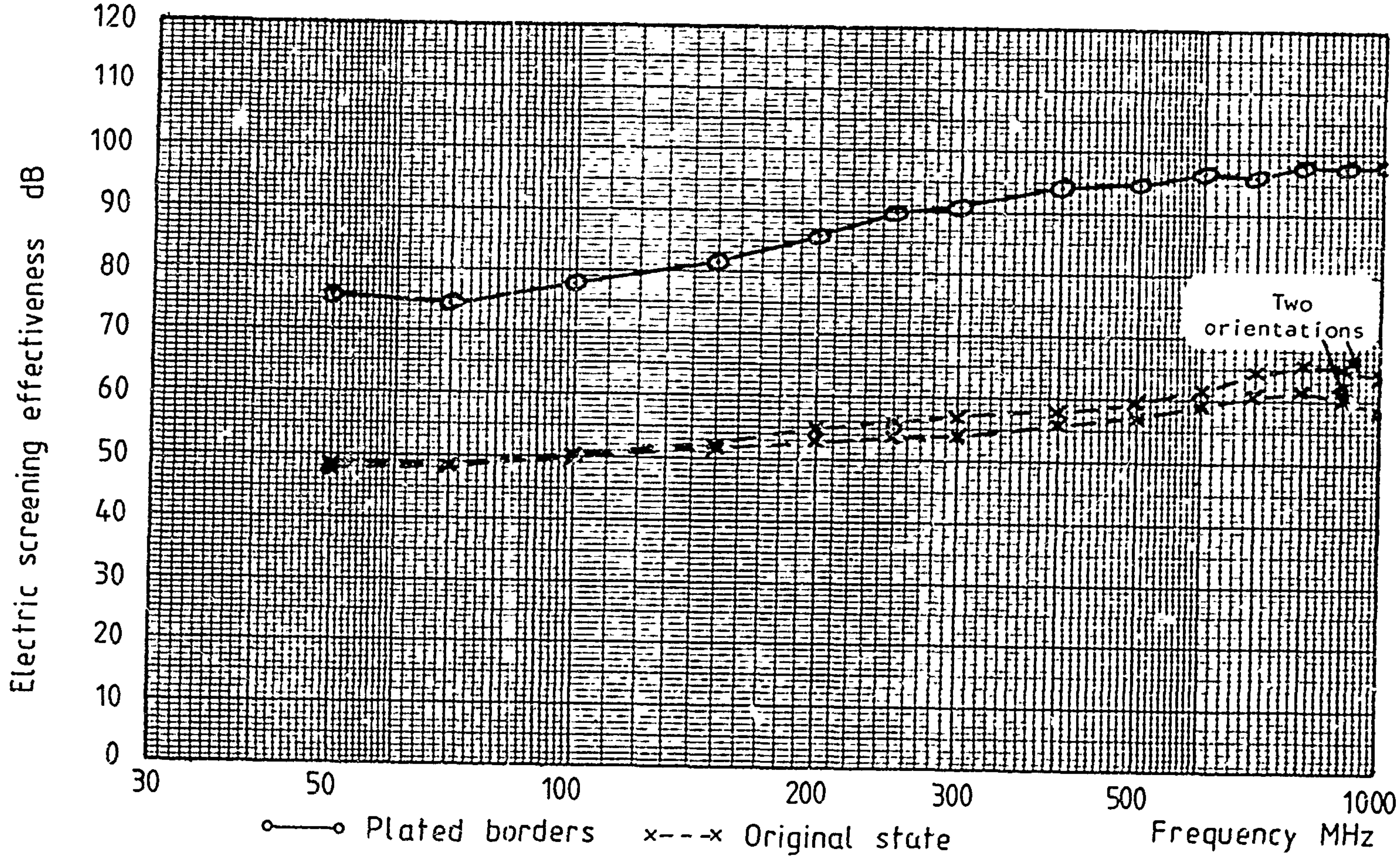


Figure 11 Electric screening effectiveness - panel W4

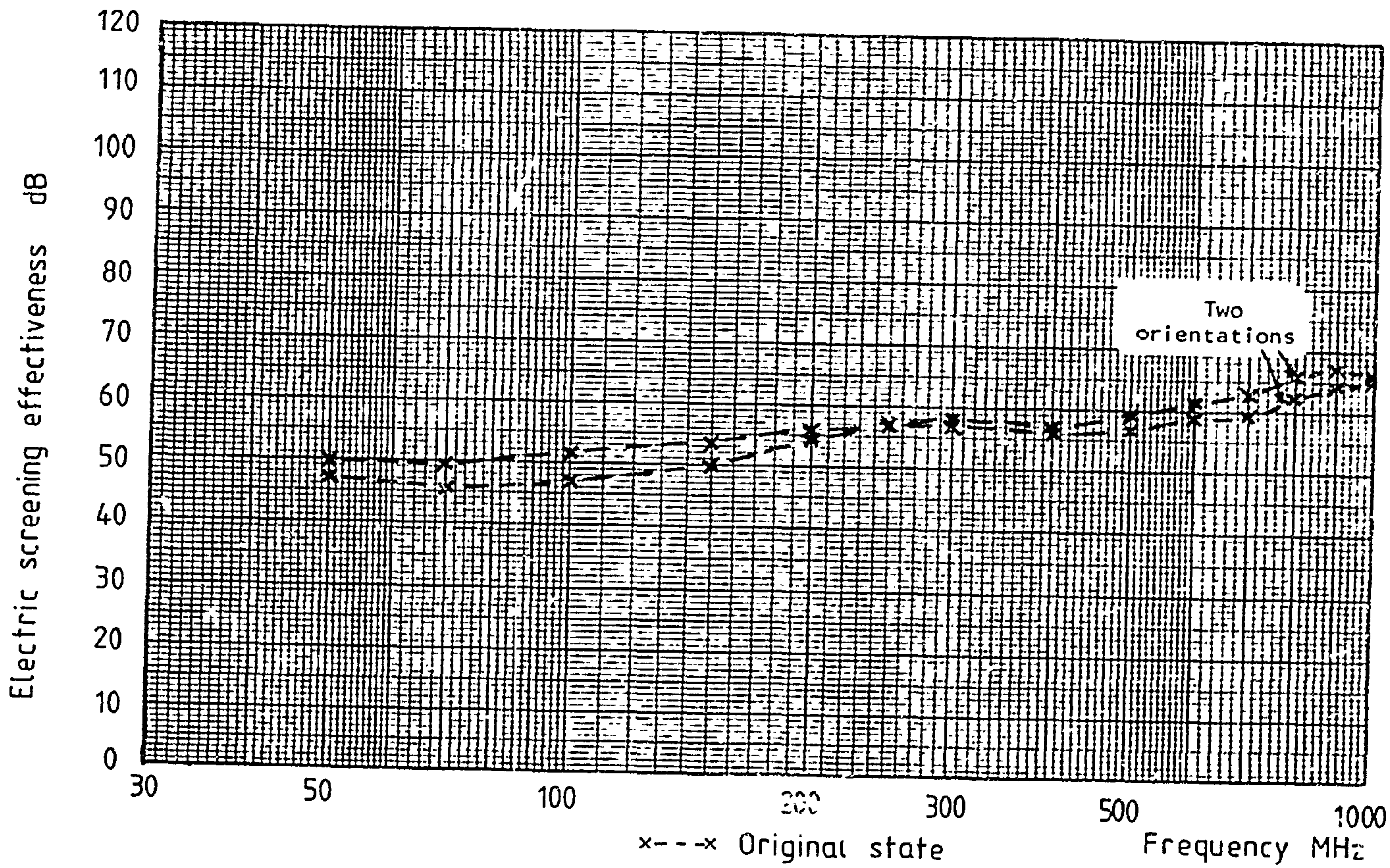


Figure 12 Electric screening effectiveness - panel W5

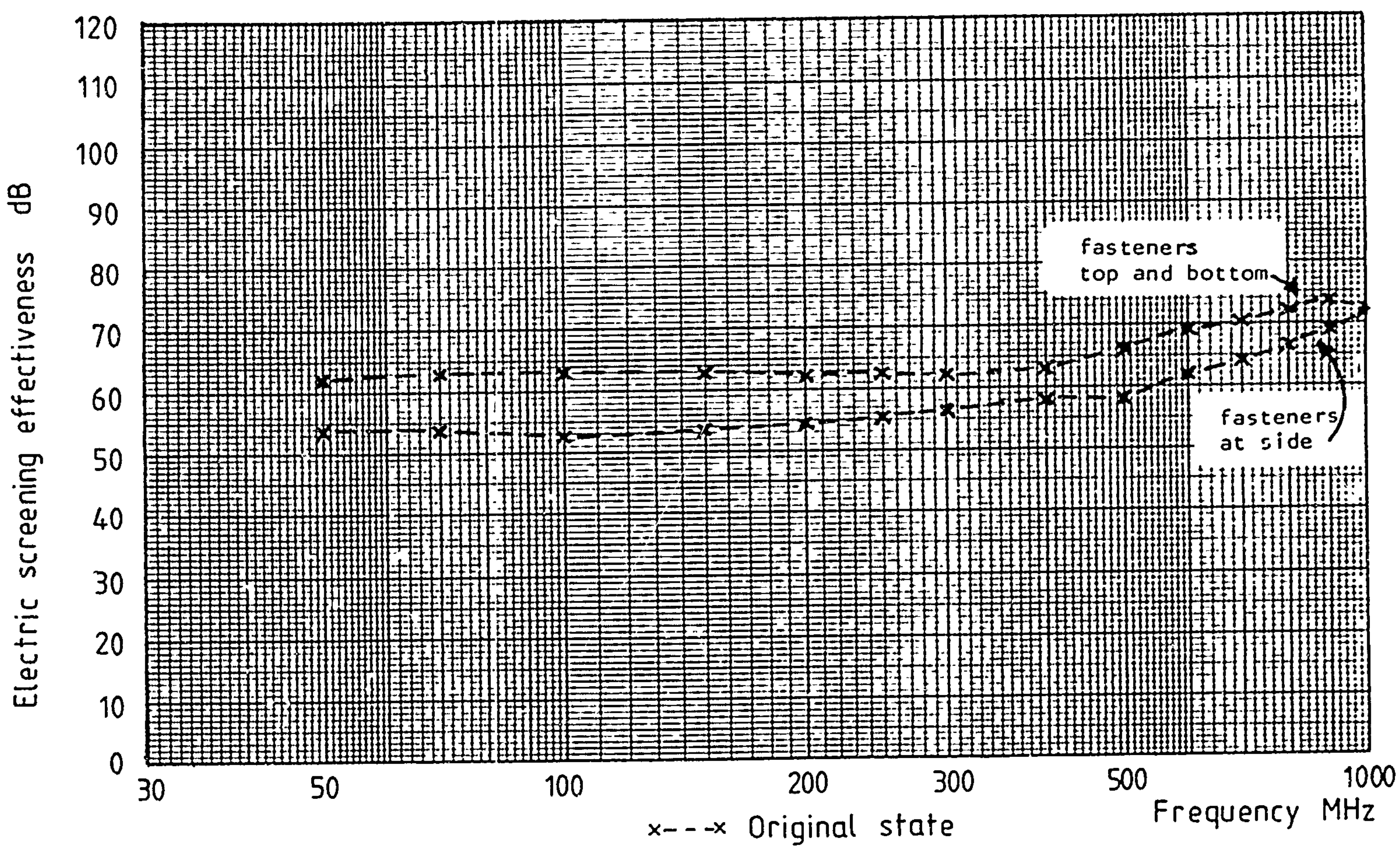


Figure 13 Electric screening effectiveness - panel W6

CHAPTER 6

ASSESSMENT OF SCREENING EFFECTIVENESS OF LOW CONDUCTIVITY PANELS

D A Bull and G A Jackson

SUMMARY

Assessment of the performance of screening enclosures constructed from high conductivity materials can generally be made by calculation from a knowledge of conductivity, screen dimensions etc. The practical performance is usually dependent on joints, seams and similar imperfections since materials such as copper and aluminium of reasonable thickness are inherently capable of providing considerably greater attenuation than is realisable in a practical structure.

This reasoning does not necessarily apply to materials of lower conductivity such as carbon fibre composites and sprayed or painted coatings of inherently lower conductivity. Calculations may not be entirely satisfactory because of inadequate knowledge of the basic parameters. Measurement of screening effectiveness is therefore important and more especially so in structures where the material of inferior conductivity is used in the form of panels in an enclosure made from high conductivity metal.

Attenuation of different panels has been measured by incorporation into one side of a one metre cubic enclosure constructed from sheet copper. The measurements were made over the frequency range from 0.15-1000 MHz and were separated into attenuation of magnetic fields in the range 0.15-30 MHz and of electric fields in the range 50-1000 MHz.

Many methods and theories have been developed in investigations into electromagnetic screening and some controversial aspects remain unresolved. It is considered that separation into magnetic and electric component measurements provides results capable of direct practical application. Furthermore although most of the work described in this report was performed under near field conditions i.e. aerial separation of one metre, measurements of attenuation were made using distant transmitters throughout the range 0.15-30 MHz and good agreement was obtained.

CONTENTS

1 INTRODUCTION

Assessment of performance of screening enclosures can be made by calculation or measurement and many papers have been written on both approaches to the subject. There is some measure of disagreement on methods of calculation, particularly of attenuation due to reflection loss which is important in considering screening materials which are either electrically thin or of inherently low conductivity, so that the loss due to absorption is not a significant fraction of the total attenuation. Measurement of performance then becomes the best way of assessing the attenuation and the methods chosen must relate directly to the application or be shown to provide results which are sufficiently independent of the conditions of measurement to be capable of use in a wide range of applications.

Most methods of measurement express attenuation as the ratio of the field strength in free space to the protected field strength inside the screen with identical separation distance between transmitter and receiver. If sufficient material is available to permit the fabrication of a complete enclosure then the measured performance will be dependent only on the characteristics of the material and the quality of the joints and seams. When screening materials are to be fitted only as panels or are of limited availability then alternative techniques must be developed. In this investigation a nominal 1 m cubic enclosure was constructed from copper sheet in which all joints had adequate overlap and were soft soldered. One face of the enclosure was left open for installation of the panel under test and means were provided to enable good contact with the test sample to be achieved.

The essential feature of the measuring technique employed was the separation into magnetic and electric mode measurements using appropriate aerial systems both inside and outside the enclosure. Most of the work was performed under near field conditions with separation of 1 m between transmitting and receiving aerials. However, in the frequency range from 0.15 to 30 MHz measurements of attenuation were also made using distant transmitters. Sufficiently good agreement was obtained between near and far field results to justify the claim that the results were capable of use in a wide range of applications.

2 CALCULATION OF SCREENING PERFORMANCE

Many methods have been devised for the estimation of screening performance. In the case of high performance screens for radio frequencies the choice of material, copper, aluminium or steel in sheet form, may be determined by mechanical or economic factors rather than for electromagnetic reasons. The calculation of screening effectiveness is straightforward in that, provided the thickness of material is significantly greater than the penetration depth at the lowest frequency of interest, the inherent attenuation provided in the screen is much greater than required or indeed measurable. The overall performance of the enclosure is then determined by the extent to which joints, seams, doors and windows can achieve low impedance contacts.

The methods of calculation described in the literature generally separate total attenuation into absorption and reflection losses. In the absorption case the estimation is based on the ratio of thickness to penetration depth. This approach is used in practically all papers on this subject and is not dependent on the characteristics of the transmitting source or the incident wave.

Estimation of attenuation produced by reflection loss is generally expressed as a ratio of wave impedance to surface impedance. The surface impedance refers to the screening structure while the wave impedance is often quoted as the value for the incident wave. Attenuation characteristics are then related to the cases of low impedance waves, high impedance waves and plane waves (Ref.17). The direct implication of this is that within the near field of the transmitter attenuation is a function of the separation distance between the source and the screen.

Miedzinski (Ref.18) developed a theory of screening based on the works of Schelkunoff and Kaden in which it was postulated that the wave impedance should be that of the secondary wave generated by induced current flow in the enclosure itself. The secondary wave impedance can be calculated from the shape and dimensions of the enclosure. The separation distance between transmitting source and receiving system is not involved nor is the ratio of tangential E and H components in the wavefront of the incident wave. It is however important that the assessment of attenuation should be

separated into magnetic and electric mode values since the pattern of induced currents differs, as is shown in Fig.1. This is the approach which has been employed in the investigations described in this report.

3 EXPERIMENTAL ARRANGEMENTS

3.1 Enclosure

The basic 1 metre cubic enclosure was constructed from copper sheet of thickness 4×10^{-4} metre with all overlapping seams soldered (Fig.2). The attenuation was estimated to be over 80 dB at a frequency of 100 kHz and over 100 dB at all higher frequencies within the range of measurement. The open face of the enclosure was provided with continuous spring loaded contacts at the four edges to enable a good low impedance joint to be obtained with the sample under test. Another enclosure was constructed entirely from copper foil of thickness 3.6×10^{-5} metre, of identical size and again with all joints overlapping and soft soldered. In this case calculation of attenuation could be made on the basis of a near perfect enclosure in which the attenuation is determined entirely by material conductivity and thickness.

Measurements were made of the attenuation provided by a panel coated with graphite, a carbon fibre composite panel and also by the thin foil enclosure.

3.2 Measuring method

Tests in the near field were made with separation distance of one metre between transmitting and receiving aerials. Identical loops were used for both aerials in the frequency range 0.15-30 MHz to cover magnetic mode measurements and identical miniature biconical aerials were developed to cover electric mode measurements in the frequency range from 50-1000 MHz. Far field tests used broadcast transmissions in the range between 0.15 and about 2 MHz. At higher frequencies small local transmitters were used with separation distance of several wave lengths. These tests covered the frequency range up to 30 MHz. The far field tests were all made in the magnetic mode using the same loop receiving aerial but employing where necessary sensitive receiving equipment designed at ERA for the detection of signals below the noise level.

The coverage of such a wide frequency range inevitably led to problems with resonance effects. The cavity resonance effects in the enclosure at frequencies around 230 MHz and above were significantly reduced by the installation of resistive damping material around the walls inside the enclosures.

4 RESULTS

The results of a wide and comprehensive investigation have been summarised in the curves given in Figs.3,4 and 5. Figure 3 relates to the performance of the one metre cubic enclosure made completely from copper foil.

The attenuation is shown in the magnetic mode in the frequency range up to 30 MHz and the measured values for near and far field conditions are compared with the calculated value. Agreement is reasonable up to about 10 MHz. The significant deviation occurs in the far field values at 15 and 25 MHz. The cause of the deviation was almost certainly a faulty connector in the receiving system.

Figure 4 shows results of measurements using loop aerials to determine the attenuation in the magnetic mode for panels of a carbon fibre composite material and an insulating material coated with graphite.

The coated panel was electrically thin over most of this frequency range and the surface impedance was not sufficiently low to provide very much reflection loss. The results for the carbon fibre panel show attenuation increasing with frequency over most of the frequency range where reflection loss is dominant, i.e., up to 3.0 MHz, and then increasing more rapidly at the higher frequencies in the range. For this sample the penetration depth was equal to the physical thickness at about 2.5 MHz. The attenuation of the CFC panel was measured under both near and far field conditions and the results show very good agreement throughout the frequency range.

Figure 5 shows the results of attenuation measurements in the electric mode using doublet and biconical aerials and covering the frequency range from 50-1000 MHz. In this frequency range difficulties were experienced with lack of sensitivity in the receiving system; broadband electric aerials which are sufficiently small to be installed in a 1 metre cubic enclosure have very small effective height. Comparisons have not yet been made under

far field conditions due to the lack of sensitivity. The method of measurement, however, has been developed to the extent that the results are useful in indicating the behaviour of the samples in the vhf and uhf bands.

Attenuation in the electric mode shows little variation with frequency and the values shown in Fig.5 for the coated panel and the composite material are almost certainly attainable down to very low frequencies. The results for the coated panel show that useful attenuation in the vhf band can be provided by the simple and inexpensive technique of painting or spraying. In the copper foil enclosure the electric mode attenuation is very much greater than the measuring capability and hence no results are shown.

5 CONCLUSIONS

The investigation described in the report has shown that a method of assessing the screening performance of various materials is available which is capable of giving results that are largely independent of the test conditions. This conclusion relates particularly to the separation distance between transmitting source and receiver but is restricted at present to attenuation in the magnetic mode in the frequency range up to 30 MHz. Nevertheless the evidence provided is a good indication that results of measurements made under near field low power conditions are relevant to far field situations. Also the evaluation of screening performance by methods involving the wave impedance of the secondary wave generated by current flow in the screen itself provides results which are not dependent on the source-receiver separation distance, contrasting with those which employ the wave impedance of the incident wave. It is considered that this method of assessment is relevant in quantifying the screening performance of both traditional metals and recently developed composite materials of the complex shapes and construction associated with surface vessels, land vehicles and aircraft.

APPENDIX

Simplified sample calculation of attenuation

Calculation of the attenuation by reflection in the magnetic mode may be made by considering the 0.9 m (nominal 1 m) cubic enclosure as a sphere for which the appropriate radius is 450 mm.

The reflection loss calculated by the methods described in Ref. 18 is then:

$$\left(1 + Z_w / Z_s\right) \quad \text{where } Z_w = \omega\mu_o \frac{a}{3}$$

$$Z_s = \frac{1}{\sigma t} \text{ or } \frac{1}{\sigma\delta} \text{ (whichever is the greater)}$$

where

t	material thickness.
ω	$2\pi f$.
σ	conductivity.
δ	penetration or skin depth.
a	radius of enclosure.
μ_o	$4\pi \times 10^{-7}$ H/m.
Z_w	wave impedance of the secondary wave
Z_s	surface impedance of the screen

The reflection loss at 1.0 MHz for the copper foil enclosure is then approximately 66 dB. The absorption loss at this frequency is small (4 dB) since the material thickness is less than the depth of penetration. The total attenuation is thus about 70 dB, a value which is not dependent on the relative locations of transmitters and receiver.

Calculation of attenuation by methods involving the wave impedance of the incident wave show reasonable agreement for low impedance,essentially magnetic,fields from, for example, a loop aerial at short separation distance (71 dB). In the case of the distant transmitter, for which the ratio E/H approaches that of free space, the estimated value of attenuation by reflection becomes very much greater e.g. 110 dB for a transmitter at a distance of 1 km.

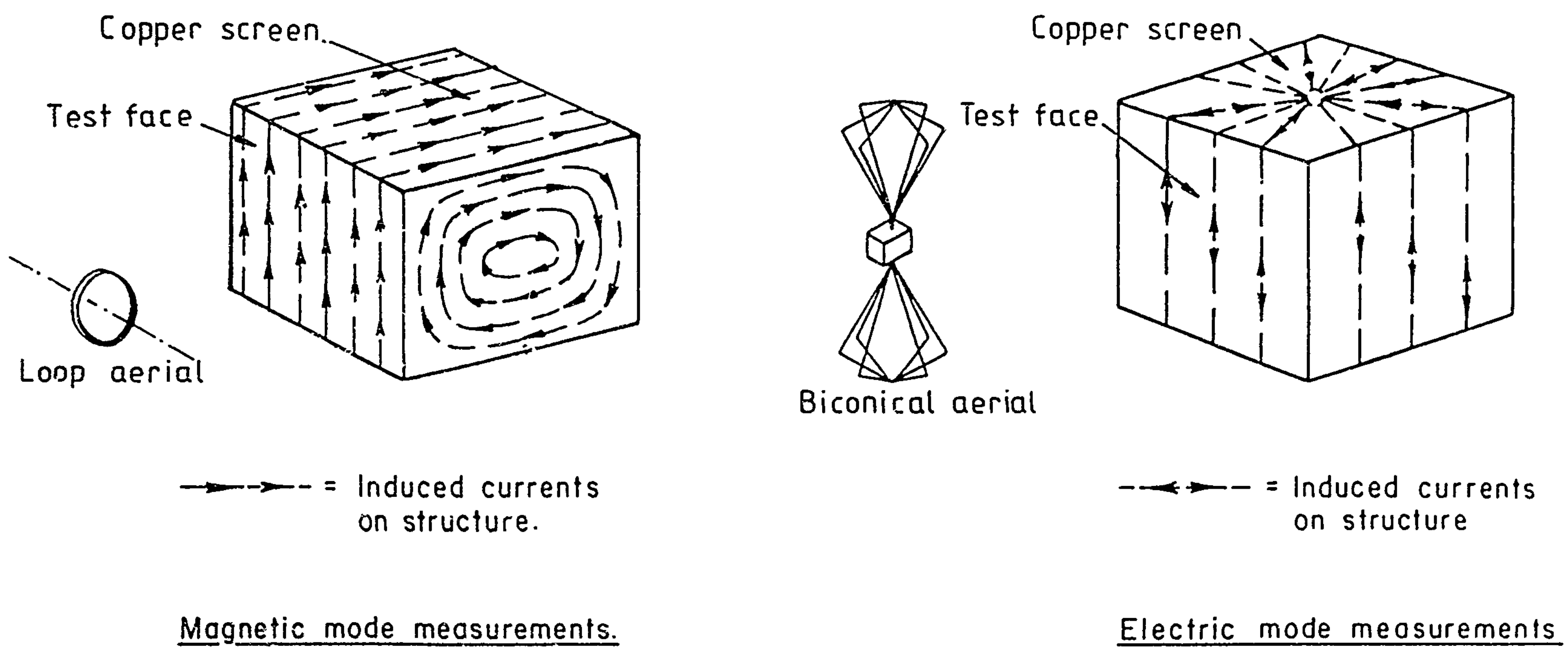


Figure 1 Current flow in magnetic and electric modes

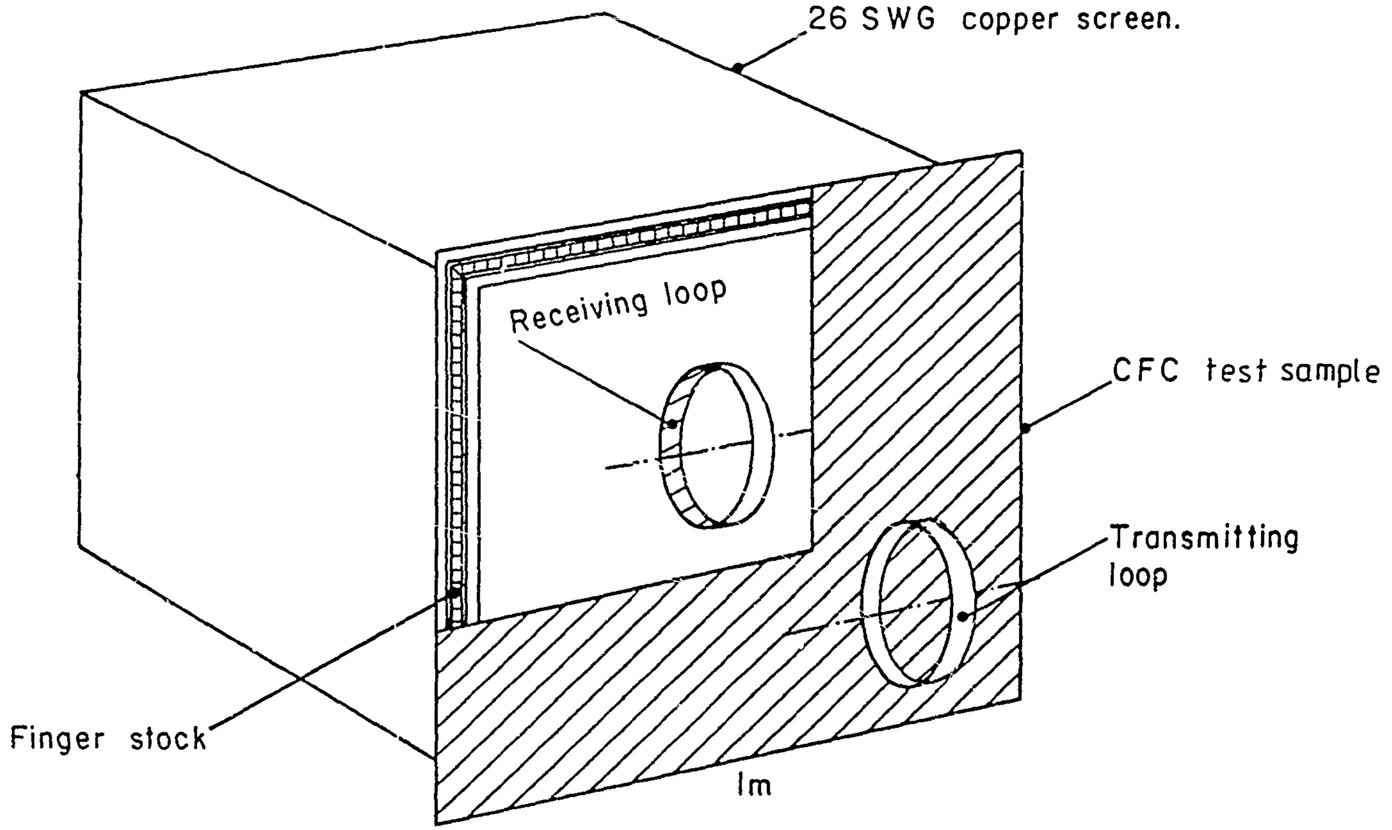


Figure 2 Configuration of the 1.0 m enclosure

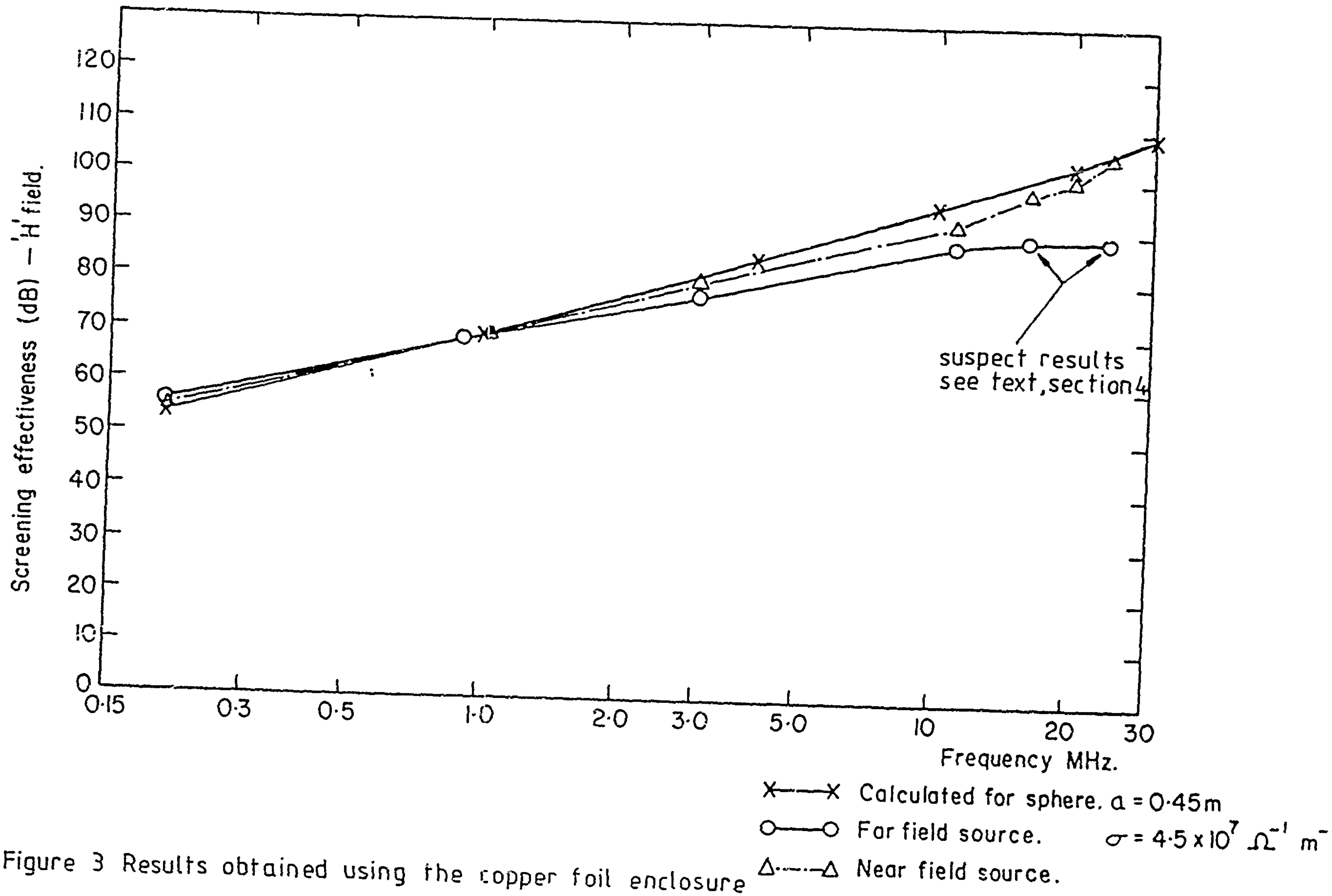


Figure 3 Results obtained using the copper foil enclosure

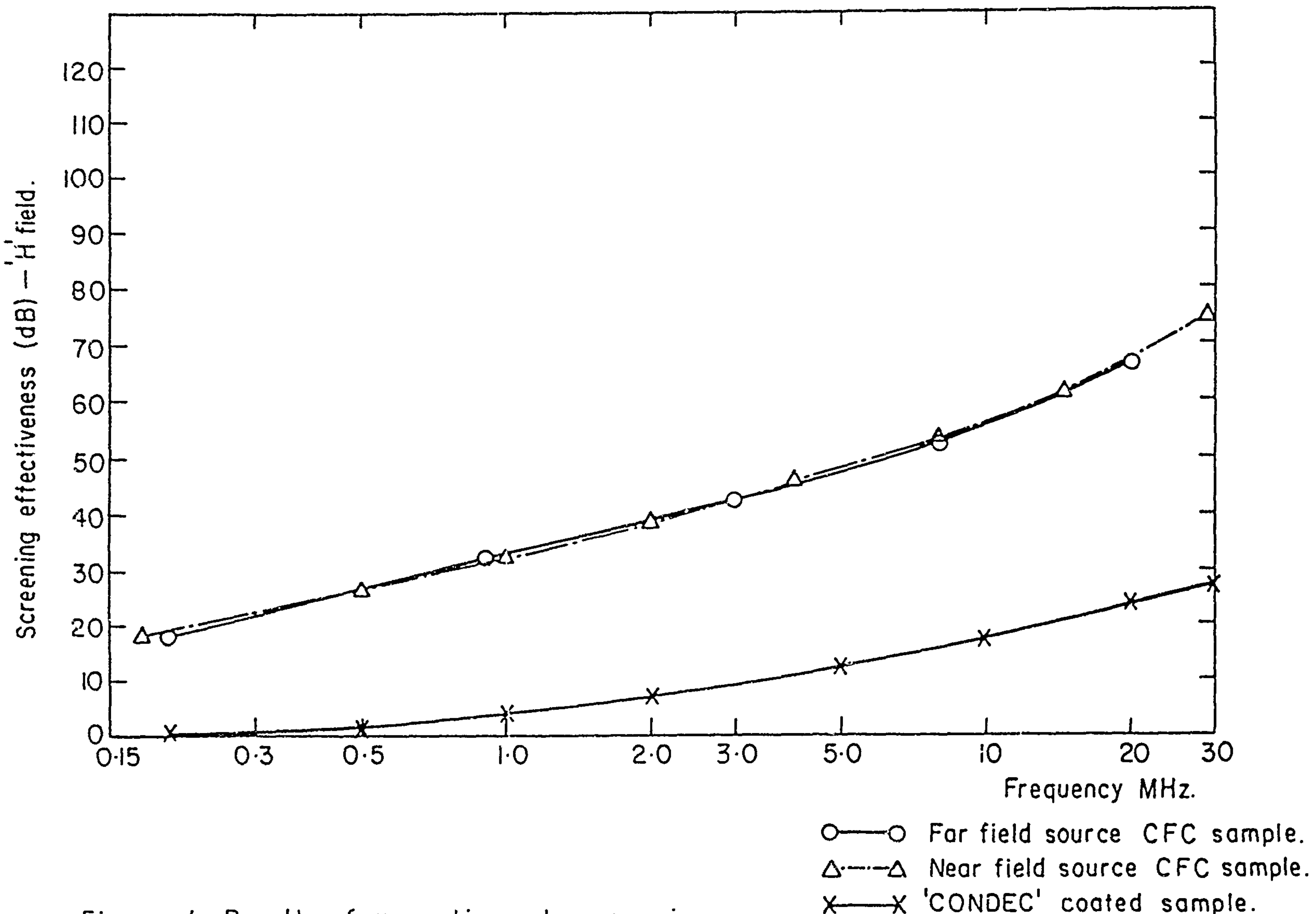


Figure 4 Results of magnetic mode screening

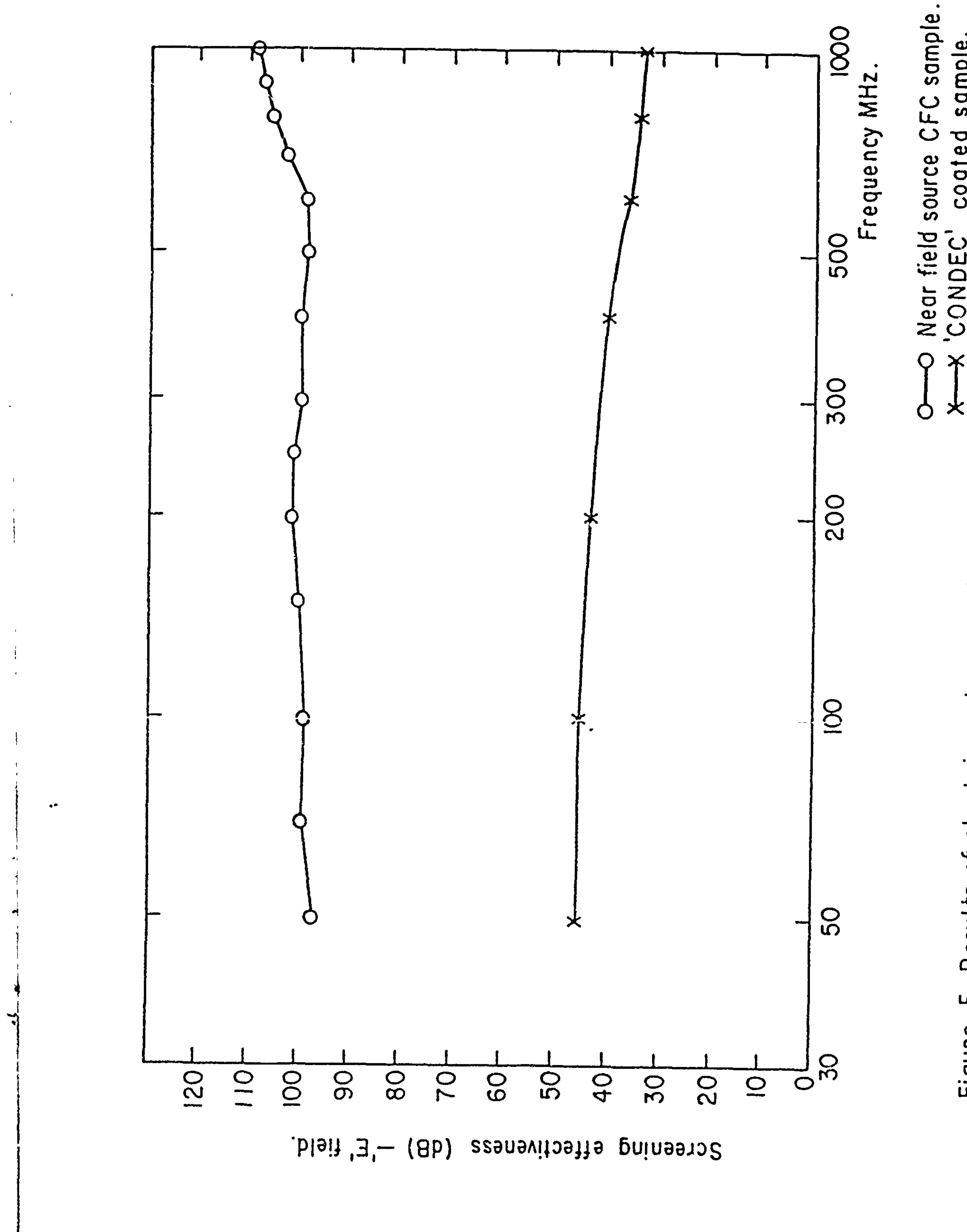


Figure 5 Results of electric mode screening

CHAPTER 7

THE ELECTROMAGNETIC ENVIRONMENT OF AN AIRFRAME PARTLY CONSTRUCTED FROM CARBON FIBRE COMPOSITE MATERIAL

A McHale

SUMMARY

One original panel section of a Wessex helicopter tail cone was replaced in turn with several demountable panels of carbon fibre composite material. Subsequent changes in the electromagnetic environment within the tail cone were investigated.

To enable variations in the screening effectiveness of different sample panels to be established much effort was directed to reduce the high fields generated in the tail cone by the helicopter's hf system.

Results of magnetic screening effectiveness, field strength and induced current measurements indicated that where electrical contact was maintained, by riveting and bolting, the screening effectiveness of both 4 ply and 16 ply panels was comparable with or greater than the screening effectiveness of the original metallic structure. Where CFC panels were mounted using adhesive bonding techniques, the screening was significantly less than for the original structure.

Electric field screening results for CFC and aluminium were comparable above 200 MHz. Between 30 and 200 MHz the adhesively bonded 4 ply CFC panel gave up to 10 dB less screening than aluminium. These results were, however, limited by the overall screening integrity of the Wessex fuselage.

CONTENTS

1 INTRODUCTION

To facilitate the investigation of the electromagnetic environment within an airframe constructed partly from carbon fibre composite (CFC) material, a time expired Wessex HAS Mk 1 airframe, XP 159, was made available by the MoD (PE).

Discussions took place between MoD (PE), Westland Helicopters Limited (Yeovil) and ERA during which it was decided to replace with CFC most of one metal panel on the starboard side of the tail cone, a section some 2 m long x 0.6 m high.

A number of suitable CFC panels was manufactured by WHL for use in this investigation.

2 SCOPE OF THE INVESTIGATION

The following aspects of the electromagnetic environment within the tail cone area were examined both before and after modifying the tail cone to take the test panels:

(a) Magnetic screening of the starboard side of the tail cone, measured using a loop source and detector, 0.15-30 MHz.

(b) Magnetic field strength from on-board hf transmissions, 2-24 MHz.

(c) Electric field strength from on-board hf transmissions, 2-24 MHz.

(d) Current induced during on-board hf transmissions on a test loom installed on the starboard side of the tail cone within the airframe, 2-24 MHz.

(e) Electric screening, 30-1000 MHz, of the starboard side of the tail cone, measured for selected test panels using miniature biconical source and detector aerials.

3 MODIFICATIONS TO THE FUSELAGE

An aperture was made in the starboard side of the tail cone by removing most of one of the magnesium alloy panels and the longerons and stringers where these crossed the aperture. The dimensions of this trapezoidal aperture were 1.8 m by approximately 0.5 m. Figures 1 and 2 show the completed aperture after edging with aluminium 'U' channel. As the tail section of the fuselage is curved, the lower edges were built up where

necessary so that flat CFC test panels could be accommodated. Screening integrity was maintained throughout this built-up region by suitably folding and bolting aluminium sheet between the 'U' channel and the fuselage. Good electrical continuity between the 'U' channel edging and the fuselage was ensured by removing all paint and other non conductive layers from the edges of the airframe panels which border the aperture. Fingerstock attached to the 'U' channel ensured good repeatable continuity between the test panels and the 'U' channel.

4 INSTALLATION OF TEST LOOM

A test loom, seen in Figs.2 and 3, consisting of 2.5 m of 300 Ω twin feeder, was installed inside the tail cone. The loom, supported by wood, was positioned horizontally along the aperture centre line and was spaced some 50 mm inside the original fuselage skin. Both ends of the loom were terminated with resistors equal to the characteristic impedance between lines. Provision was made to clamp a current probe around one or both lines along the loom.

5 MODIFICATIONS TO THE HF SYSTEM

The hf aerial on the Wessex consists of a double wire which runs along each side of the cabin and tail cone areas. The wire passes beneath the aircraft at the rear of the tail cone and is centre fed at this point from an unscreened feeder. The feeder passes through the tail cone floor and connects to the Aerial Tuning Unit (ATU) at the rear of the tail cone. Three screened cables, two coaxial and one control (multiway), run along the port side of the tail cone and connect the ATU to the transceiver located in the radio compartment of the nose structure.

One major part of this investigation was to examine the screening performance of the fuselage to transmissions from the on-board hf system. It was found, however, that radiation from unscreened and poorly bonded parts of the hf system within the tail cone masked the required results. The following steps were therefore taken to minimise coupling paths other than by penetration through the fuselage in general and the test panels in particular:

(a) The aerial feeder was repositioned to run vertically down through the fuselage skin close to the ATU. The repositioned aerial feeder can be seen in Fig.2.

(b) The ATU and aerial feeder (where it runs inside the fuselage) were totally enclosed within an aluminium screened enclosure. The feeder was passed through coincident holes in the fuselage and the base of the screened enclosure. The enclosure (Fig.3) was well bonded to the fuselage by a number of short solid copper straps.

(c) The three screened cables from the ATU were taken through close fit holes (bulkhead fittings were not possible) into the ATU enclosure. The screens of these cables were grounded to the fuselage close to the ATU enclosure using short copper braid straps (Figure 3).

(d) The UR 67 single-screened coaxial cable carrying rf power from the transmitter to the ATU was replaced within the tail cone and rear cabin by a 9 m length of 'superscreened' (otherwise equivalent to UR 67) cable and for the rest of the fuselage length by double-screened RG 214/U.

(e) The outer braids of all the coaxial cables entering the tail cone and rear cabin areas were bonded together and grounded immediately forward of the tail cone/rear cabin and the rear cabin/main cabin bulkheads. The grounding straps (25 mm width copper braid) were kept as short as possible. The braid screen on the ATU control cable was also grounded at these points. The 'superscreened' cable braid was grounded both near the ATU and near the rear cabin/main cabin bulkhead.

Early measurements had revealed a number of resonances occurring within the hf band. These resonances were associated with the lengths of various coaxial cables and tended to enhance the field at certain frequencies. By bonding the cable screens at several places the resonance frequencies were shifted to above 30 MHz. The 'superscreened' cable, however, was required to be kept intact for other investigations and so could only be grounded at each end of its 9 m length. Under these conditions this cable was found to resonate at 12 MHz. A number of results were affected by the resonance at that frequency; however no further measures were taken to reduce the effects as it was considered useful to show the degradation of the electromagnetic environment resulting from such a cable resonance.

Initial screening measurements showed the screening for the tail cone area to be poor (for an all metal structure) and this was likely to

mask differences between results for the test panels. The airframe was originally manufactured using a 'wet skin' construction technique and as a consequence the various layers of sealant and paint, etc. precluded good electrical continuity between adjacent panels. To improve the screening, the edges of overlapping panels were cleaned to bare metal and solid copper bonding straps, 25 mm x 50 mm, were bolted across the seams. A number of these straps are visible in Fig.4. The straps were placed at approximately 0.4 m intervals along all vertical and horizontal seams between panels in the tail cone and rear cabin areas. The inclusion of these bonding straps improved the fuselage screening (as measured through the port side of the airframe) by more than 15 dB throughout the hf band.

6 TEST PANELS

Six CFC test panels were supplied by Westland Helicopters Limited. These panels were attached to aluminium 'picture frames' using adhesive bonding, bolting and riveting techniques. The test panels, suitably mounted on the picture frames, were in turn clamped to the aluminium 'U' channel which edged the aperture.

Figure 5 shows the basic configurations and dimensions of these panels. Other parameters are listed below:

Fibre	:	XAS
Resin	:	BSL 913
Lay-up	:	3 panels of 4 ply $\pm 45°$ (relative to panel centre line) with 70 mm wide borders built up to 24 ply.
	:	3 panels of 16 ply $\pm 45°$ (relative to panel centre line)

One of each type of panel was mounted on an aluminium 'picture frame', Fig.5, using each of the following techniques:

Adhesive bonding	:	Ciba-Geigy Araldite 2001 cured at room temperature
Bolting	:	5 mm titanium bolts with 100° countersunk angle, 28 mm pitch and cadmium plated steel nuts
Riveting	:	0.125 in. stainless steel self-plugging rivets pitched at 25 mm (Avdel Type 4051-0411)

A 20 gauge aluminium sheet was also used to obtain comparative results.

Titanium bolts are scarce in the UK so consequently there were insufficient to fasten both bolted panels simultaneously at the predetermined pitch. It was decided therefore to fasten the 4 ply panel fully and use the remaining bolts on the 16 ply panel. There were sufficient bolts to fill approximately alternate holes of the 16 ply panel (holes pitched at 28 mm). Earlier tests had shown screening results for the 16 ply panel with every bolt included to be similar to results for the same panel with every fourth bolt. It was therefore considered that alternate bolts, i.e. at a pitch of 56 mm, would give results representative of the panel with a full complement of bolts.

7 MEASUREMENT TECHNIQUES

7.1 Screening by loop source method

Screening measurements were made in the magnetic mode over the frequency range 0.15-30 MHz. The test configuration is shown in Fig.6. The source was a 0.25 m diameter loop excited by a RF Power Labs M102L wideband amplifier and an Advance SG 200 signal generator. A 6 dB 50 Ω attenuator was included between the amplifier and the loop to protect the amplifier output stage from impedance mismatch.

The source loop was located outside the tail cone (Fig.1) and the detector, a portable 'H' unit consisting of a 0.25 m diameter loop and a tuned head amplifier, was located within the tail cone (Fig.7). The portable 'H' unit output was measured using a Schwarzbeck 1515 measuring receiver.

Measurements were made with the loops in co-planar orientation, with the detector located on the tail cone centre line. The source was excited at each test frequency and the signal received within the tail cone was measured. It was confirmed, by rotating the detector loop, that the maximum transfer, for the loops separated by the test panels, occurred when the detector was in the same orientation as the source, i.e. the polarisation of the applied field was not significantly affected by the inclusion of the test panels. Centre to centre separation between the loops was 2 m.

The signal transfer between the loops at 2 m separation was also measured over an unobstructed path, i.e. well clear of the aircraft and other reflecting objects.

The screening effectiveness of the tail cone with the various test panels interposed between source and detector is defined as:

$$\frac{\text{Signal transferred over the unobstructed path}}{\text{Signal transferred through the test panel mounted on the tail cone}}$$

Screening results were obtained at positions A and B on the tail cone centre line as identified in Fig.5.

Figure 7 shows the portable 'H' unit at position B.

7.2 Field strength from hf transmissions

The field strength from on-board hf transmissions was measured within the tail cone using a 0.5 m doublet aerial (i.e. an electrically short dipole) at position A for electric field and using a 0.14 m diameter loop at both positions A and B for magnetic field. Each detector was connected via a balanced-to-unbalanced transformer to a Singer Stoddart NM 17/27 measuring receiver. The fields at each frequency and each position were measured in three orthogonal planes and the vector sum taken to obtain the resultant maximum electric or magnetic field. The transmitter used for the field and induced current measurements was the helicopter's Collins 618T which was operated in the 'AM' mode without modulation.

7.3 Induced current from hf transmissions

The current induced in the test loom during on-board hf transmissions was measured using a Stoddart 94111-1 current probe and Singer Stoddart NM 17/27 measuring receiver. The current probe was clamped round both wires midway along the test loom as shown in Fig.8.

7.4 Field Strength from on-board vhf and uhf transmissions

The field strength from transmissions in the vhf and uhf aircraft communications bands using aerials mounted on the test panels was measured within the tail cone. The uhf transmissions used the on-board ARC 52

transmitter operating into a Chelton 16-11-P1 blade aerial and the vhf transmissions used a Marconi TF 2015/1 signal generator operating into a brass monopole which was cut to be quarter-wave resonant at 127 MHz. The field strength was measured using a miniature biconical aerial together with a Singer Stoddart NM 37/57 receiver.

The field strength was measured for five uhf and three vhf frequencies and at three positions along the tail cone centre line.

At each position the field strength was measured for three orthogonal orientations of the biconical aerial. The three measurement positions have been identified in Fig.5.

7.5 Electric field screening

Electric field screening in the range 30-1000 MHz was measured for a number of the test panels. Figure 6 shows the test configuration.

Two ERA designed miniature biconical aerials were set up, one on the centre line of the tail cone and the other outside the tail cone, 2 m from the first. The source aerial was fed from either a Marconi TF 2015/1 signal generator, 30-500 MHz, or TF 1060 signal generator, 450-1000 MHz. A 2 W amplifier was used to increase the source power between 30-100 MHz. The detector aerial was used in conjunction with a Singer NM 37/57 measuring receiver.

The electric field screening was measured with the biconical aerials set up at positions A and B as identified in Fig.5.

The screening effectiveness of the tail cone with the various test panels interposed between source and detector is defined as:

$$\frac{\text{Signal transferred over an unobstructed path}}{\text{Signal transferred through the test panel mounted on the tail cone}}$$

8 RESULTS

To facilitate comparison of results for various panels, a number of curves are shown in each figure. Results for bolted and riveted panels were, in all cases, virtually identical and so, to simplify the figures, the curves for the bolted and riveted 4 ply panels have been combined, as have those for the 16 ply panels.

8.1 Magnetic field screening

Figure 9 shows the screening of the original fuselage when measured at position A through each side of the tail cone.

The two sides of the tail cone gave similar screening in the original state. The third curve in Fig.9 shows the screening of the port side after improving the bonding between the fuselage panels by the inclusion of some 80 copper straps attached over the whole tail cone and rear cabin skin area. 15-20 dB improvement was obtained throughout the frequency range. The inclusion of further bonding straps might have further improved the overall fuselage screening; however the present degree of improvement was thought sufficient to allow differences to be clearly seen between the various test panel results in terms of the screening, field strength and induced current measurements.

The minimum in the curve at 8 MHz was due to a resonance of the hf wire aerial. Grounding one or both ends of the aerial eliminated the effect. Most results obtained at position A were affected in this way.

Figures 10 and 11 give the screening results for positions A and B respectively. Results are shown for each CFC panel and also for the aluminium sheet. These results highlight the following points:

(a) There was no significant difference between the screening performance of bolted or riveted panels (at the designate pitch centre diameters used in this investigation).

(b) The 16 ply panels, bolted or riveted, gave typically 10 dB more screening than the equivalent 4 ply panels.

(c) At frequencies above 8 MHz the 16 ply (bolted or riveted) panels and the aluminium sheet gave comparable results. At these screening levels the screening appeared to be limited by the overall integrity of the fuselage rather than by the test panels.

(d) The use of adhesive bonding substantially degraded the screening performance of both 4 ply and 16 ply panels. Below 12 MHz the 16 ply panel offered less screening than the 4 ply panel.

(e) Comparison of Figs.9 and 10 shows the bolted and riveted CFC panels to offer greater screening over much of the normal operational hf band than had been afforded by the original magnesium alloy skin. The degree of screening obtained using the adhesively bonded panels is, however, less than that obtained in the original state.

8.2 Field strength within the tail cone from on-board hf transmissions

Figures 12 and 13 indicate the magnetic field strength measured for each panel at positions A and B respectively.

The effect of the resonance of the 'superscreened' cable can be seen at 12 MHz, particularly for the results obtained at position A. The general trend of these results agrees with screening results (Figs.10 and 11) in that:

(a) Riveted and bolted panels give virtually identical results.

(b) 16 ply riveted and bolted panels give greater screening than the equivalent 4 ply panels. At position A, where the hf wire aerial passes nearest to the panel, the internal field strength is expected to show greatest dependence on the panel screening characteristic. The difference between the field strength measured for the 4 ply and 16 ply panels is 10 dB which corresponds to the difference between the screening results in Fig.10.

(c) The field strength within the tail cone was greatest for the adhesively bonded panels. Little difference was shown between the 4 ply and 16 ply panels except above 12 MHz where the 4 ply panel gave up to 10 dB higher field strength.

(d) Results for the 16 ply bolted and riveted panels and the aluminium panel were similar at frequencies above about 12 MHz.

Figure 14 shows the field strength at position A for the original magnesium alloy skin and unscreened hf system. This result is compared with the final modified state, i.e. aluminium panel attached to the aperture rim together with a fully screened and bonded hf system. Cable resonance effects at 4.5 MHz and 12 MHz can be seen. The original 4.5 MHz resonance was removed by bonding the coaxial cables. Comparison of the original configuration results, shown in Fig.14, and the results

in Fig.12 justified the decision to screen and bond the hf system as the field strength from the unscreened hf feeder would have otherwise masked all differences between the results for the various panels shown in Fig.12.

Also included in Fig.14 are field strengths measured both for the open aperture, i.e. no panel attached, and also external to the tail cone. This latter value was measured in line with position A at the same distance beyond the hf wire as between the hf wire and the tail cone centre line. This value approximates to the field strength that would be measured at position A if the fuselage were to provide no screening. Comparison of these external values and the field strength measured within the tail cone gives an indication of the screening offered by the tail cone.

Figure 15 shows the electric field strength measured at position A for the various conditions. The field strength for the original unscreened condition was a maximum of 10 V/m at position A, being considerably higher than that measured for the 4 ply adhesively bonded panel. Close to the unscreened ATU and aerial feeder the field strength exceeded 100 V/m.

The electric field results show similar trends to the magnetic field results although the differences in the values measured for the aluminium and both 4 and 16 ply (bolted and riveted) panels are less marked throughout the frequency range.

The maximum electric field occurred at the 12 MHz cable resonance and was not dependent on the type of test panel.

8.3 Induced current from hf transmissions

Figure 16 shows the induced current measured on the test loom. Results show the following similarities with the magnetic field strength and the screening results:

(a) Identical results from bolted and riveted samples.

(b) Induced current for the 16 ply bolted and riveted panels was 10-12 dB lower than for the equivalent 4 ply panels.

(c) The induced current was greatest for the adhesively bonded panels. These two panels gave similar levels between 2 and 12 MHz but differed by about 10 dB above this frequency.

8.4 Field strength from on-board vhf and uhf transmissions

Table 1 lists the maximum field strength measured at each position in the tail cone for the various test panels. Similar field levels were measured for each test panel although the field distribution varied from panel to panel. The CFC panels gave, by a small margin, the higher field strengths, i e. 2 V/m at vhf and 2.5 V/m at uhf.

8.5 Electric field screening

The measured electric screening characteristic for each panel was found to fluctuate with frequency due to reflections within the tail cone. These fluctuations made comparison of results difficult, and so, to enable comparison to be made, the screening curves have been smoothed out by applying the formula given in the Appendix B to Chapter 4. In addition to the results given in Figs.17 to 19, Table 2 lists the minimum measured screening value for each test configuration.

Figures 17 and 18 show the screening measured at positions A and B for the original magnesium alloy fuselage and also for three test panels. Additional results for position A are included in Fig.19. These additional tests were carried out after the electrical bonding between adjacent panels in the tail cone skin had been improved by the inclusion of the 80 copper straps (see Section 5). By comparison of Figs.17 and 19 it can be seen that this additional bonding has also increased the electric field screening by up to 15 dB at 30 MHz and 2-3 dB at 1000 MHz.

From the results in Figs.17 to 19 and Table 2 the following can be seen:

(a) The screening of the original Wessex tail cone was poor with a maximum value of 54 dB at 100 MHz and a minimum measured value of 17 dB at 700 MHz.

(b) At frequencies above 200 MHz the test panels (excluding the original fuselage) gave very similar results.

(c) Between 30 and 200 MHz the 16 ply CFC bolted and riveted panels gave results comparable to those for the aluminium sheet. The 4 ply CFC adhesively bonded panel (both for the simulated and finalised bond) gave screening results typically 10 dB worse than the aluminium. The 4 ply riveted panel gave an intermediate result, some 5 dB worse than the aluminium panel.

Screening effectiveness was not measured for the 4 ply bolted and 16 ply adhesively bonded panels; however these panels are expected to give results similar to the 4 ply riveted and 4 ply adhesively bonded panels respectively.

9 COMPARISON BETWEEN THE WESSEX AND COPPER ENCLOSURE RESULTS

During earlier investigations, described in Chapter 4, the screening effectiveness of 1 m^2 CFC panels was measured with these panels incorporated as one face of a cubic copper enclosure.

To enable direct comparison between screening measurements for the Wessex and for the copper enclosure, three 1 m^2 4 ply samples were supplied by WHL. These panels were attached to the copper enclosure by identical techniques to those used on the Wessex, viz adhesively bonding, riveting and bolting the built-up panel edges to aluminium 'picture frames' which were in turn clamped to the enclosure.

In Fig.20 the screening results for 4 ply riveted/bolted panels on the Wessex are compared with the equivalent results for the copper enclosure (panels P14 and P15, from Chapter 4).

Additional screening factors for the Wessex configuration are also included. These are derived from induced current and magnetic field strength measurements from the on-board hf transmitter.

Figures 21 and 22 show the same series of results for the 4 ply adhesively bonded and 16 ply riveted/bolted panels. In the latter case the results for the copper enclosure refer to the 16 ply panel P9(a) with copper plated borders since no 16 ply 1 m^2 panels were available for riveting and bolting.

Four screening curves are shown in each figure. These are:

(a) Measurement of screening by loop source and detector, as in Section 7.1.

(b) Measurement of screening by loop source and detector for 1 m^2 panels incorporated as one face of a cubic copper enclosure. Full details and results are given in Chapter 4 of this report.

(c) A screening factor obtained by comparing the magnetic field from hf transmissions measured at position A inside and also outside the tail cone. This latter position was level with the internal position A and at the same distance beyond the hf wire aerial as between the hf aerial and the internal position A.

(d) A screening factor obtained by comparing the current induced on the test loom measured with and without the test panels in position.

In all three figures there is generally reasonable agreement between the results. The causes of a number of the discrepancies have been identified as being due to the construction of the helicopter and are:

(a) At 8 MHz, the value of screening measured by the loop source and detector is reduced due to the fundamental resonance of the Wessex hf wire aerial. This wire passes close to the propagation path between source and detector. Grounding this wire at one or both ends eliminates the effect and the screening value at 8 MHz is increased to follow the general trend of the curve.

(b) At 12 MHz a cable resonance, see Section 5, enhances the magnetic field and consequently reduces the 'screening' result based on the magnetic field measurements. Induced current measurements are also affected by this cable resonance.

(c) The induced current measured on the test loom under open aperture conditions (Fig.16) shows a minimum at 14 MHz which depresses the induced current 'screening' results around this frequency in Figs.20-22. The use of the 'open aperture' condition is not ideal as the screening effects of the remaining fuselage on the test loom are not known. However, apart from the minimum around 14 MHz,

> the screening results obtained by this method show good agreement with the other results. Closer agreement around 14-18 MHz is obtained by linearly interpolating between points on either side of the minimum in the 'aperture' results of Fig.16.

The screening measured by the loop source method for both the Wessex and copper enclosure configurations gave similar results, although the copper enclosure tended to give the lower screening values. This is probably due in part to there being a greater proportion of CFC on the enclosure than on the Wessex. A comparison of the panel widths shows the path impedance across the 1 m^2 panels to be a factor 1.5 times greater than for the Wessex panels and on this basis, the screening values would differ by about 4 dB. This being so, one would expect a structure comprised of a greater proportion of CFC to give reduced screening. The adhesively bonded panels, where the high impedance joints are the dominant factors influencing the screening, show the closest agreement between the Wessex and the enclosure and also the least difference between 4 ply and 16 ply panels.

Results of electric field screening for 1 m^2 CFC panels, incorporated as one face of a copper enclosure, are also included in Chapter 4. The results, for a variety of panels, indicate essentially constant screening between 30 and 1000 MHz with, depending on the quality of electrical contact at the edges, values of between 50 and 100 dB. Screening results for the Wessex (Figs.17-19) however are limited by the overall screening integrity of the fuselage to a maximum value of about 60 dB between 30 and 100 MHz, falling to about 30 dB by 1000 MHz. No valid comparison can therefore be made between the electric field screening results for CFC panels mounted on the Wessex and those for CFC panels mounted on the copper enclosure.

10 CONCLUDING REMARKS

The results of screening, field strength and induced current measurements for the various CFC panel configurations are in general agreement and indicate that:

(a) Where electrical contact was maintained by riveting or bolting the CFC panels to the fuselage via the mask or 'picture frame',

the screening of both 4 ply and 16 ply panels is comparable with or greater than the screening of the original metallic structure.

(b) Where the CFC panels were adhesively bonded, the screening effectiveness was significantly worse than for the original fuselage.

(c) It is likely that structures having a larger area of CFC will exhibit a decreased screening performance, particularly if the electrical bonding between CFC sections is poor as in the case of adhesively bonded structures. The screening performance of such structures will be further degraded by impedance discontinuities such as doors, windows, etc.

Techniques are available to minimise the adverse effects of high field strength in the hf band as a consequence of transmissions. These techniques include the screening and bonding of the ATU together with bonding and grounding of the power, signal and control lines between the ATU and transceiver.

Electric field strength within the tail cone, from vhf and uhf transmissions using aerials mounted on the test panels was some 2-3 dB higher for the CFC panels than for the aluminium panels.

Electric field screening results for CFC and aluminium were comparable above 200 MHz. Between 30 and 200 MHz the adhesively bonded 4 ply CFC panel gave up to 10 dB less screening than the aluminium panel. The screening results were, however, limited by the overall screening integrity of the Wessex fuselage.

On the basis of the above results it is unlikely that electromagnetic compatibility at vhf and uhf will be significantly more difficult to achieve on an airframe constructed largely from CFC than on a conventional metallic structure, particularly if adhesive bonding techniques are avoided.

Table 1

Field strength inside tail cone from on-board transmissions for various test panels

Frequency band and conditions	Position	Maximum field strength (dB µV/m)		
		20 gauge aluminium	4 ply CFC with simulated adhesive bond	16 ply CFC bolted
118-136 MHz:	A	123	120	119
10 W into vhf monopole	B	125	126	126
	C	122	124	123
225-400 MHz:	A	125	128	128
ARC52 into Chelton	B	124	125	123
16-11-P1	C	125	126	123

Table 2

Minimum measured electric screening for various test panels(30-1000 MHz)

Test panel	Position A		Position B	
	Frequency MHz	Minimum screening dB	Frequency MHz	Minimum screening dB
Original magnesium alloy skin	700	22	700	17
20 gauge aluminium	250	23	250	23
4 ply CFC simulated adhesive bond	500	22	250	22
16 ply CFC bolted	250	21	900	27
Additional Tests*				
20 gauge aluminium	900	24	-	-
4 ply CFC adhesive bond	900	26	-	-
4 ply CFC riveted	800	25	-	-
16 ply CFC riveted	800	28	-	-

*After the screening integrity of the tail had been improved by the inclusion of bonding straps between fuselage skin sections.

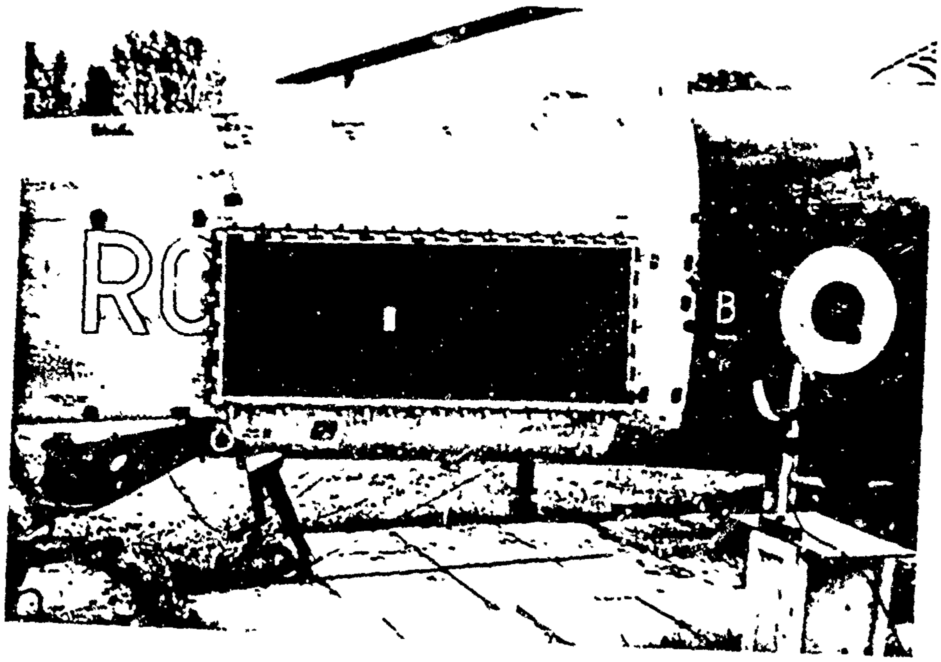


Figure 1 Modified Wessex tail cone showing mounted test panel

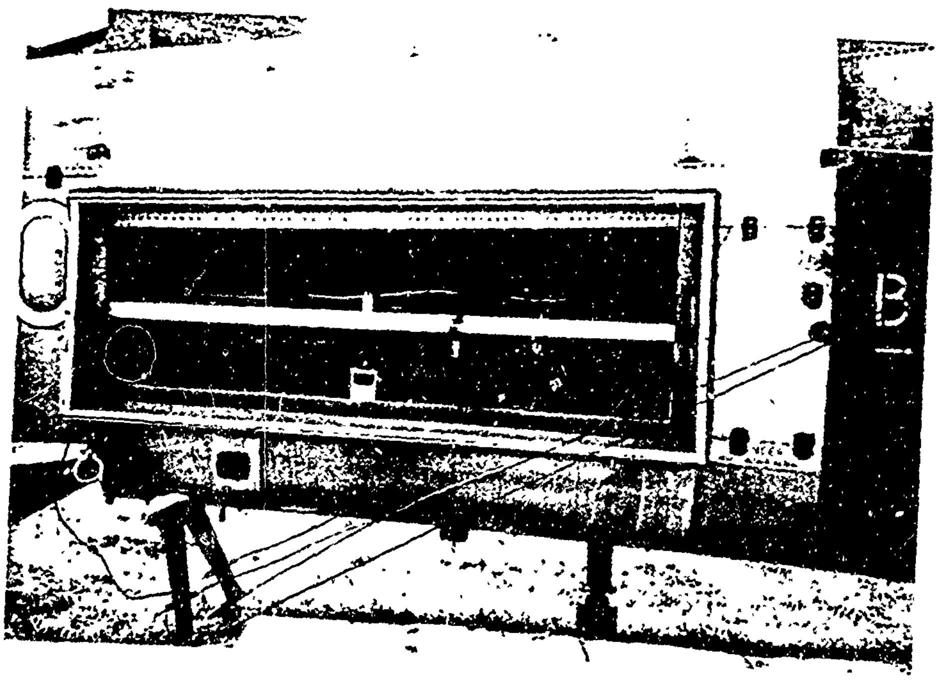


Figure 2 Modified Wessex tail cone without test panel

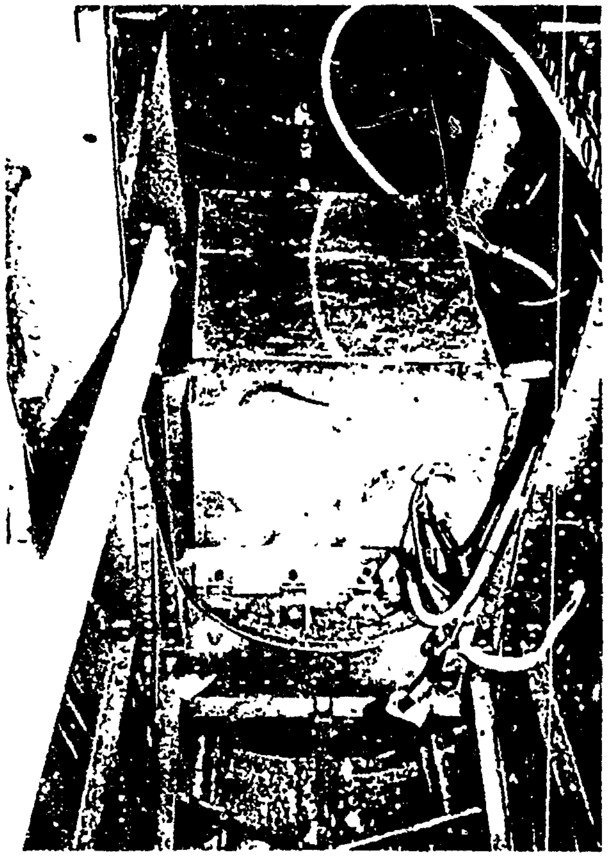


Figure 3 Test loom and the screened enclosure housing the ATU.

Figure 4 Bonding straps and built-up corner of aperture rim.

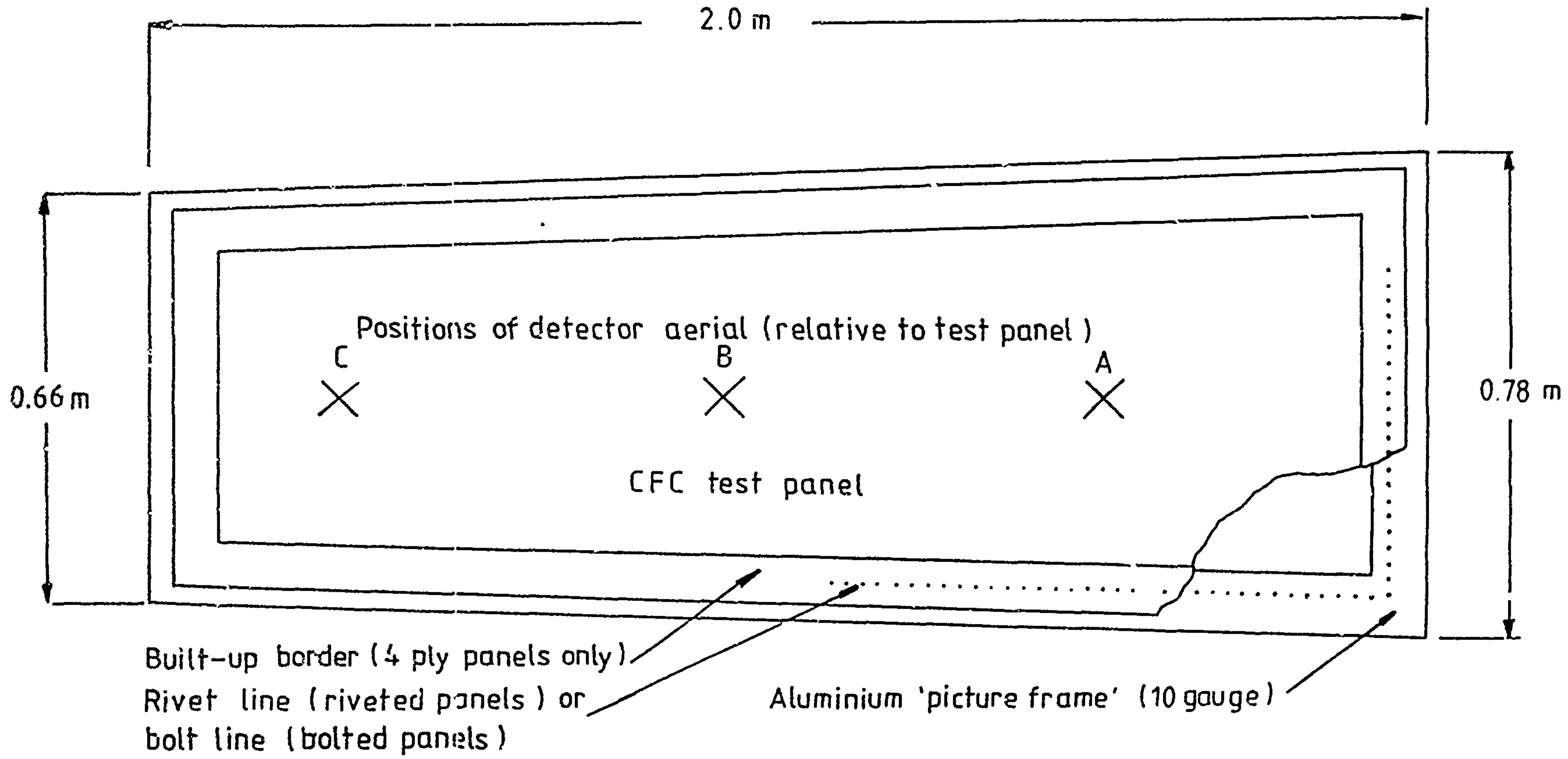


Figure 5 Test panel configuration

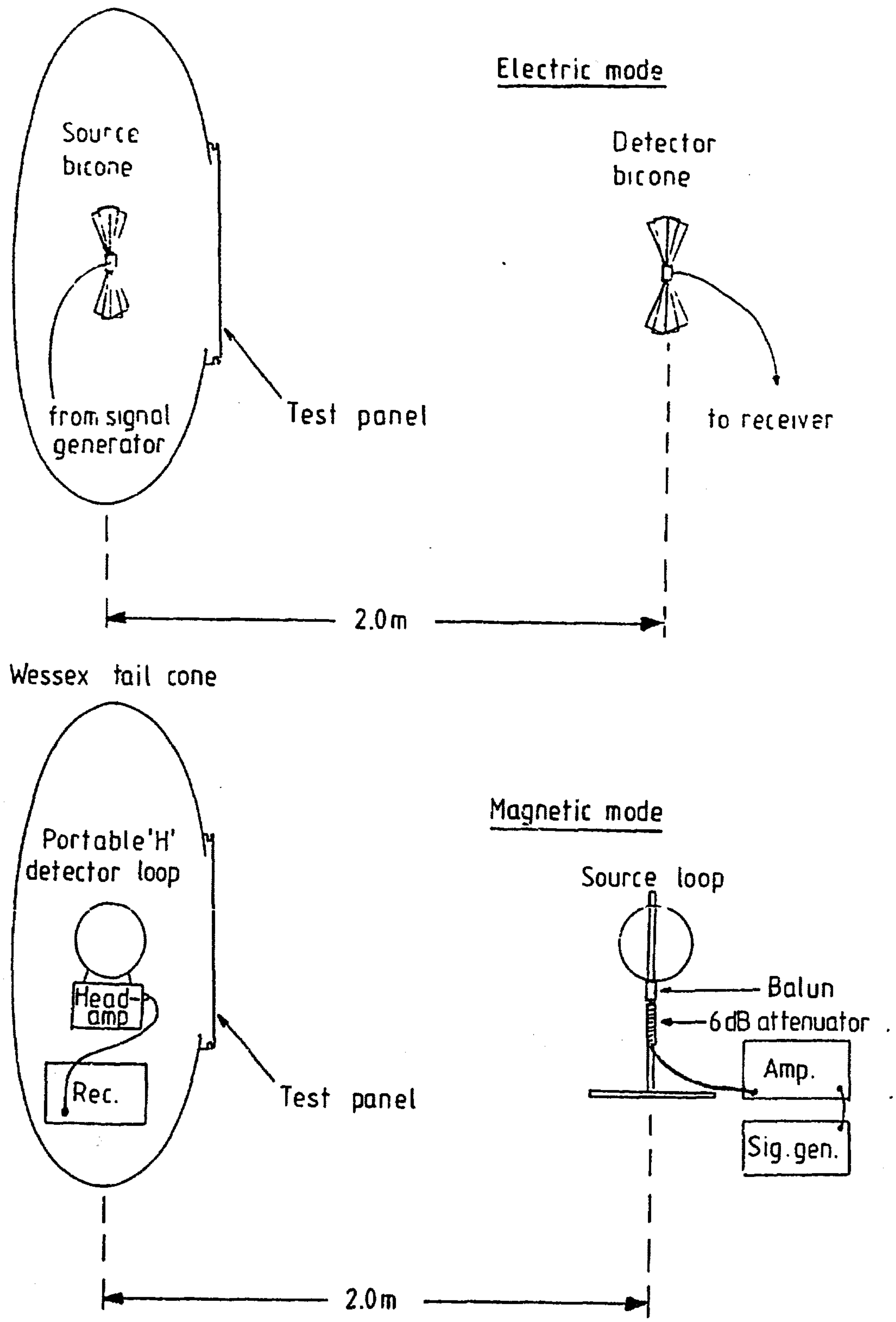


Figure 6 Configurations for screening measurements

Figure 7 Portable 'H' Detector unit at Position B

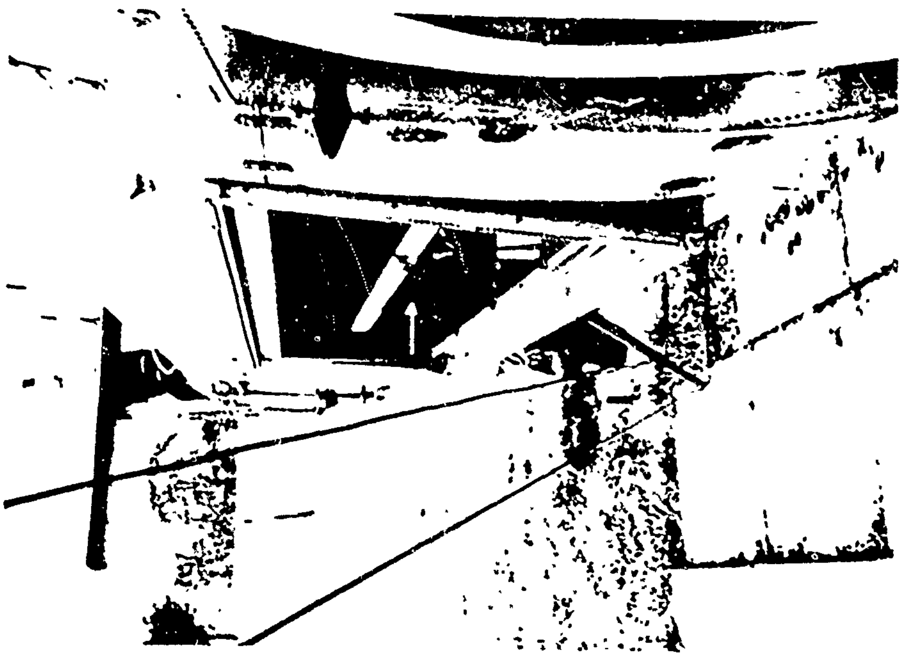


Figure 8 Current probe on test loom

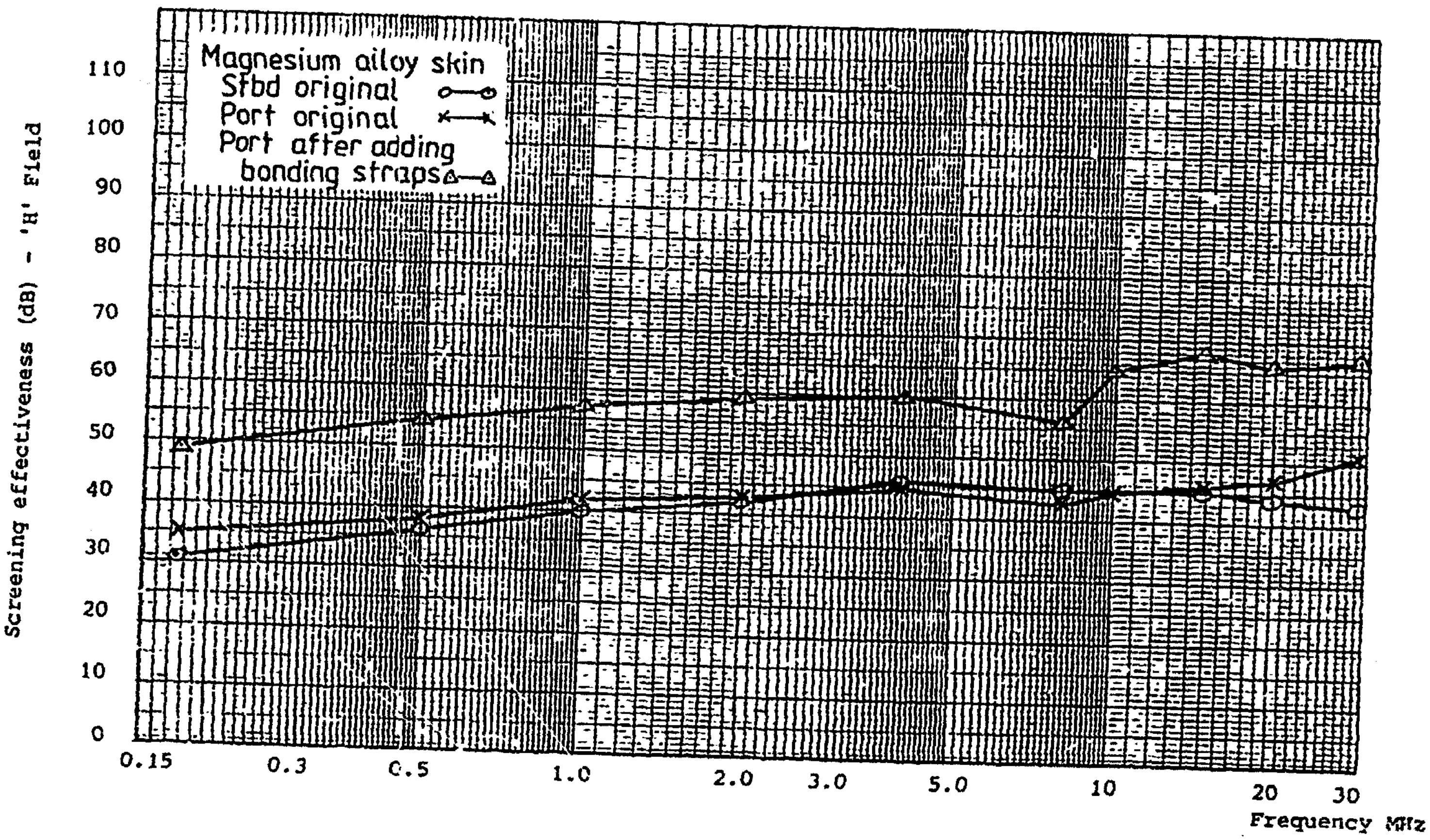


Figure 9 Screening effectiveness - magnetic mode - position A

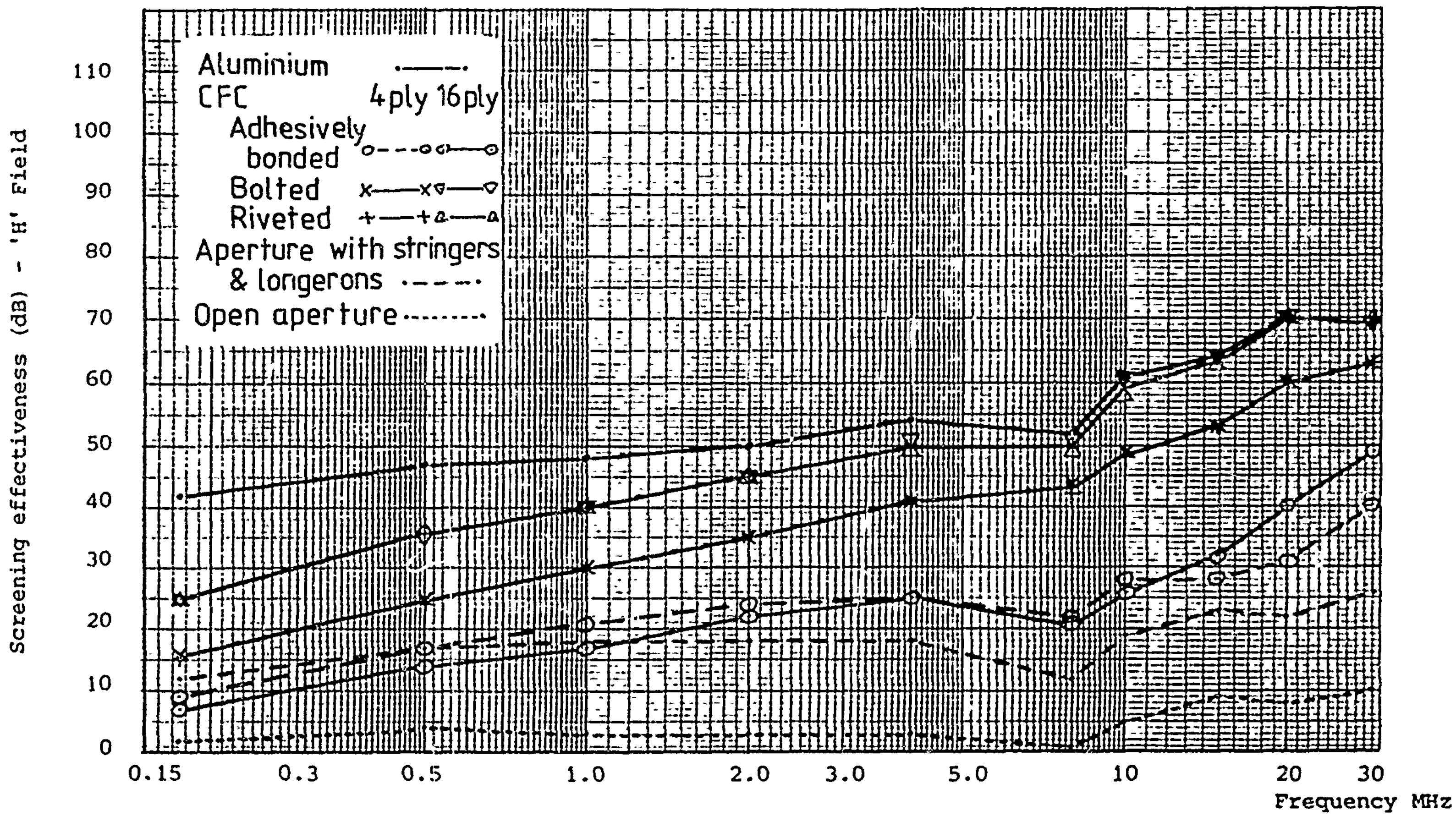


Figure 10 Screening effectiveness - magnetic mode - position A

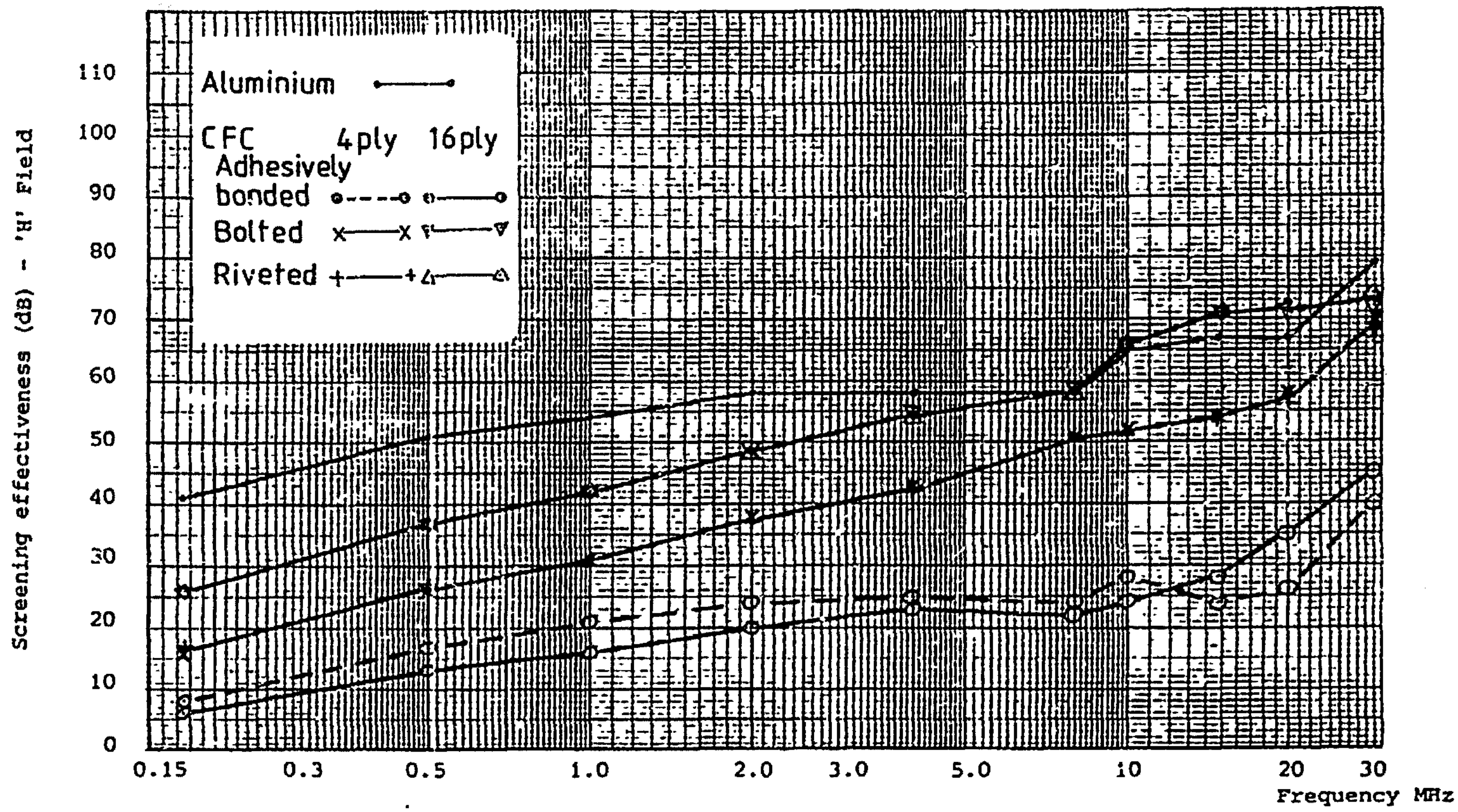


Figure 11 Screening effectiveness – magnetic mode – position B

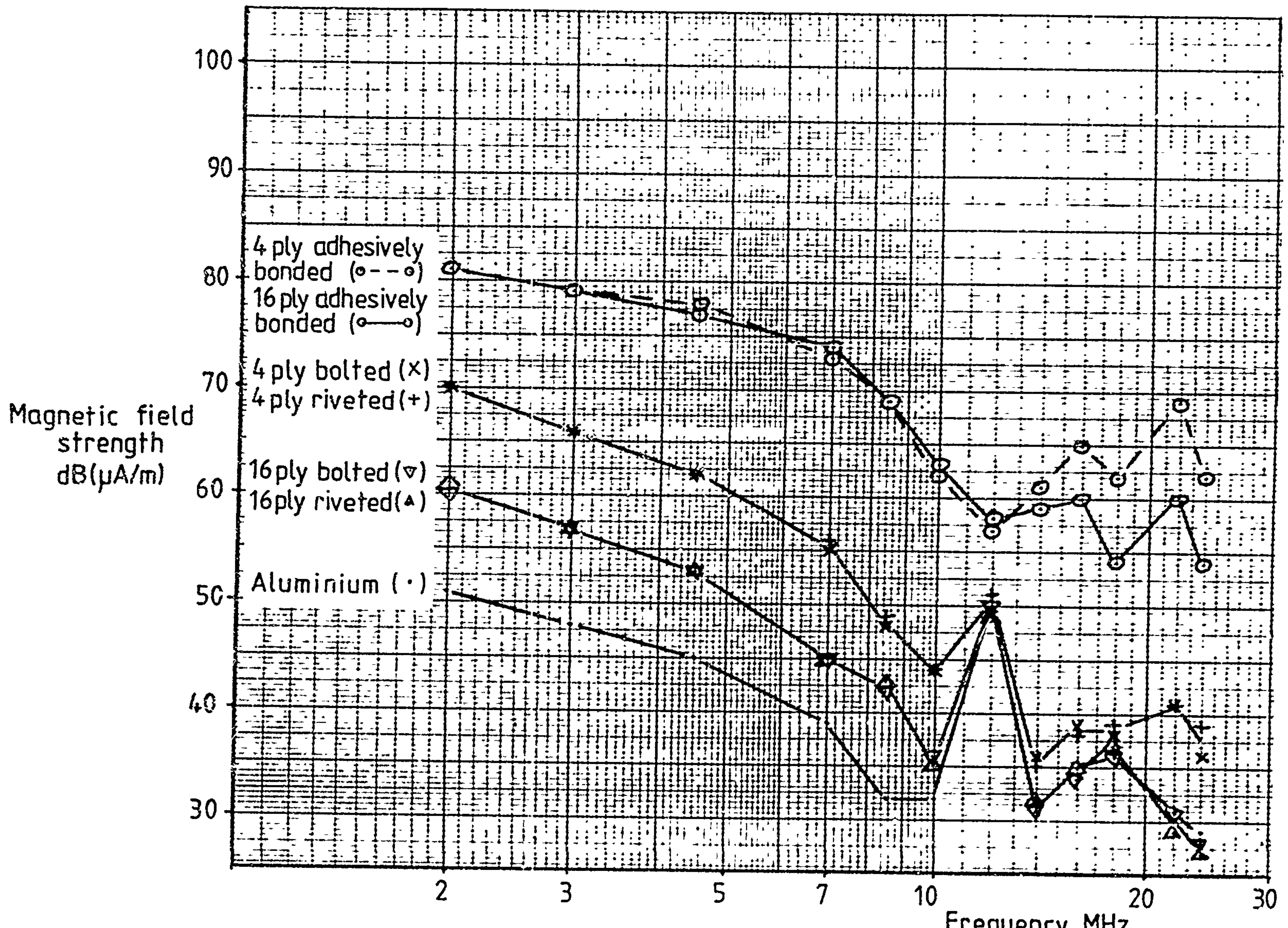


Figure 12 Magnetic field strength in tail cone during hf transmissions - position A

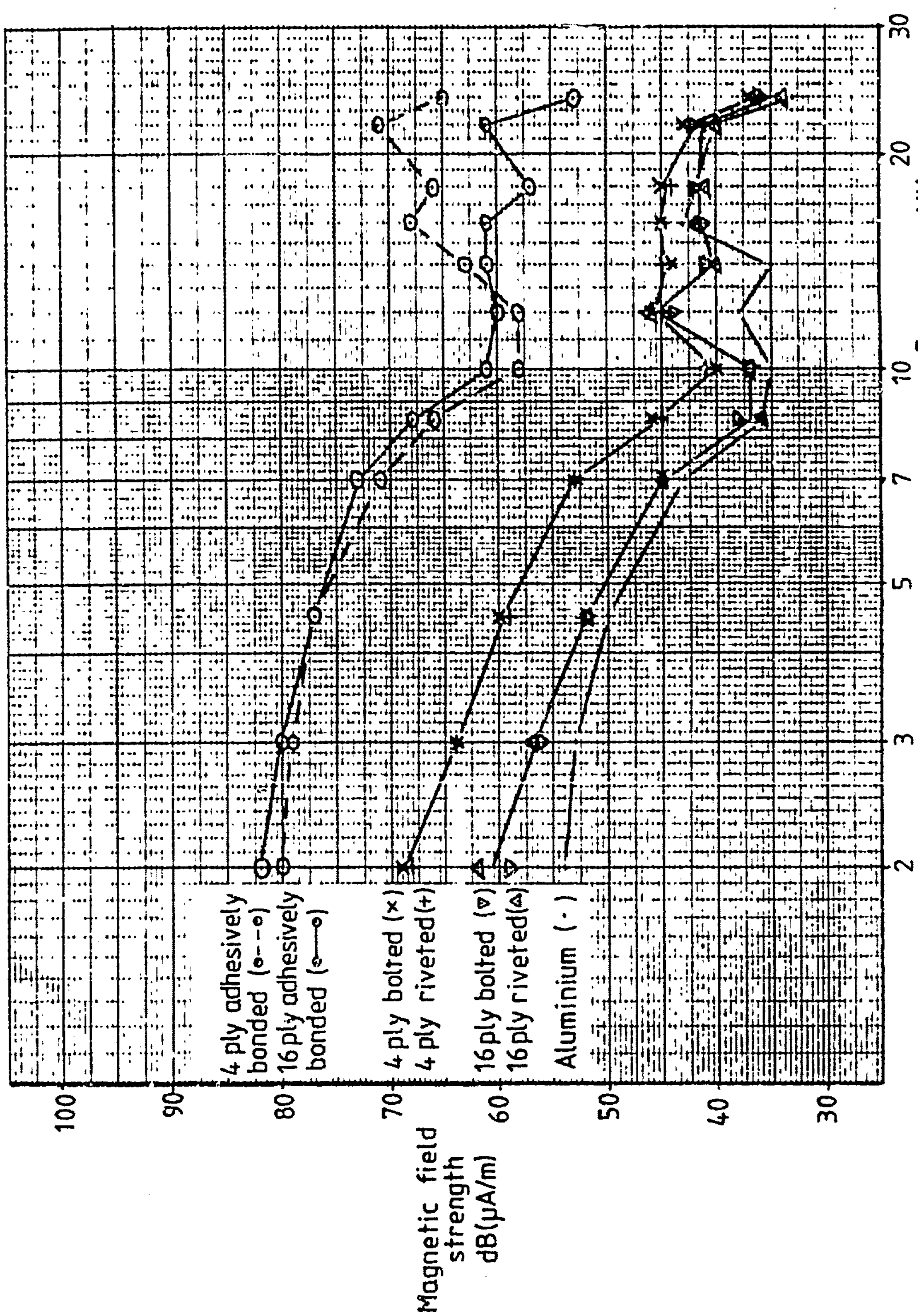


Figure 13 Magnetic field strength in tail cone during hf transmissions - position B

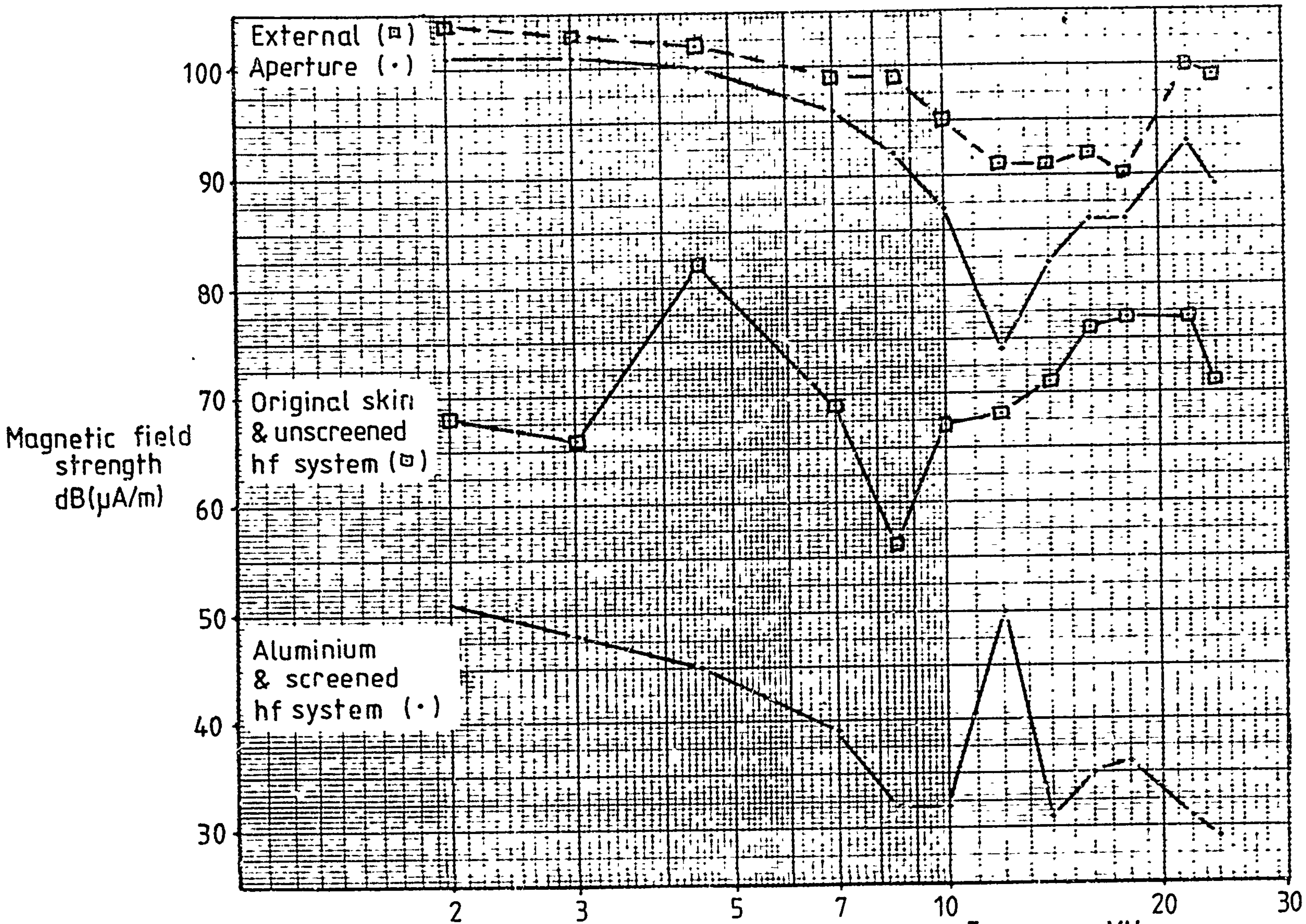


Figure 14 Magnetic field strength in tail cone during hf transmissions - position A

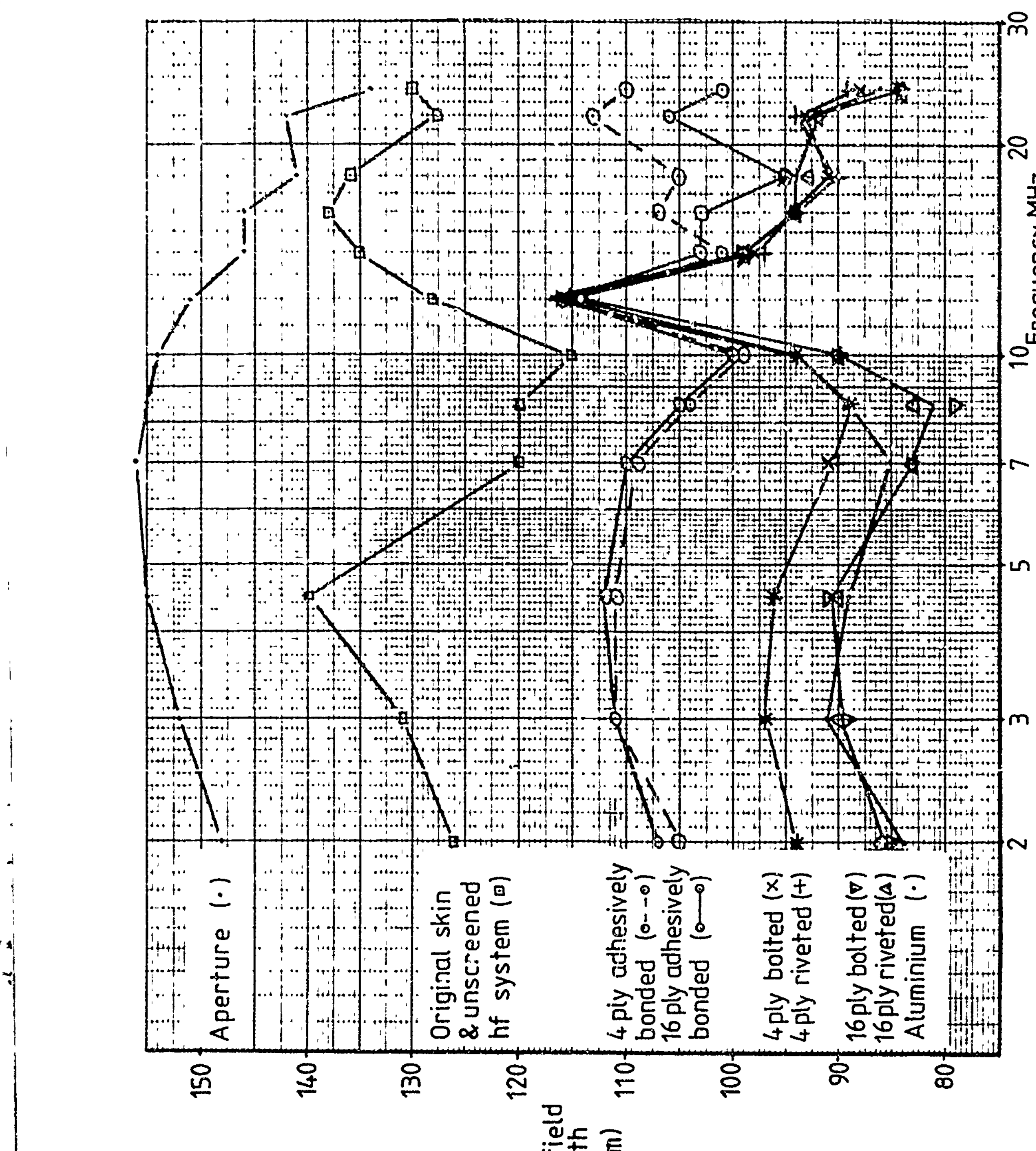


Figure 15 Electric field strength in tail cone during hf transmissions - position A

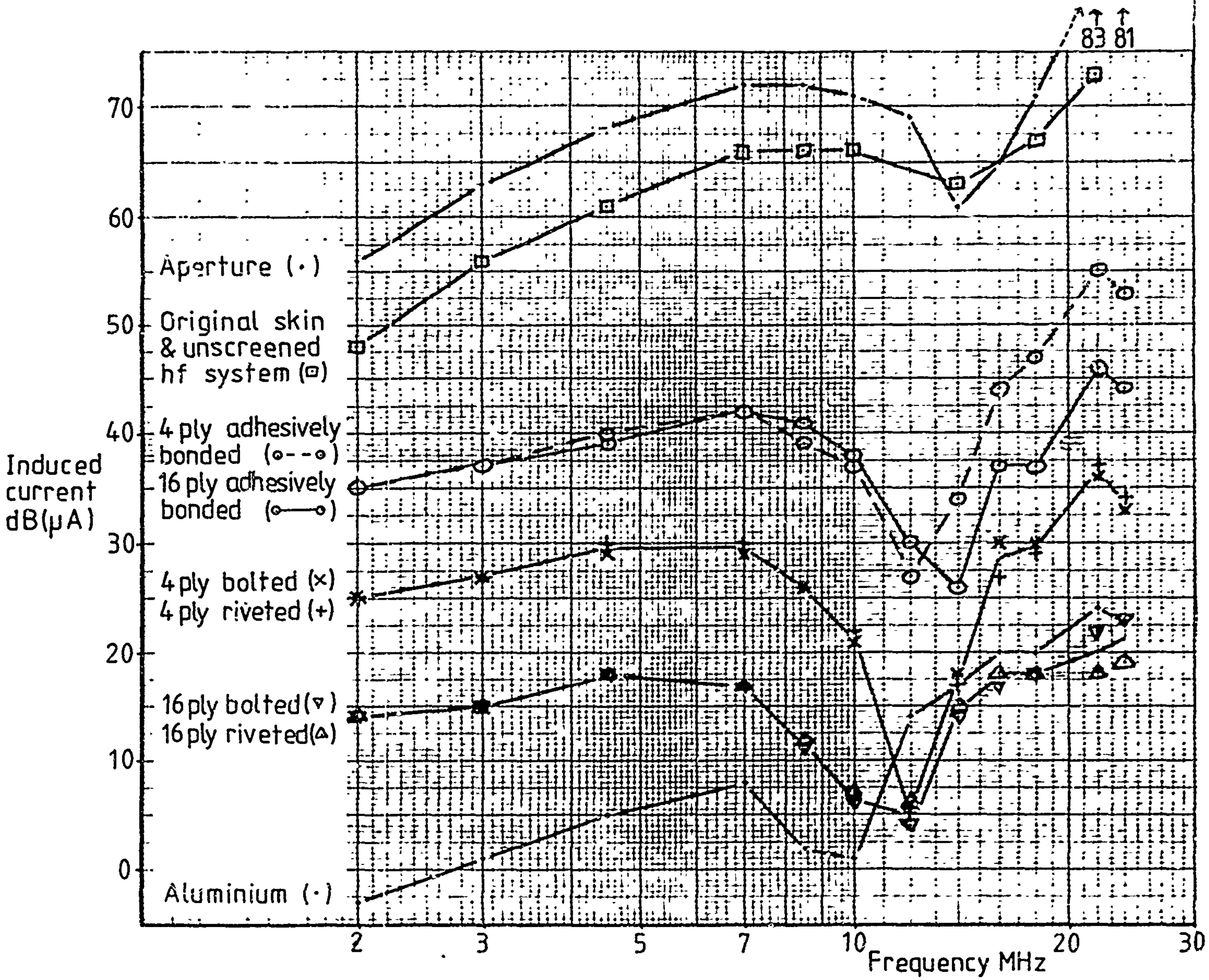


Figure 16 Induced current on test loom during hf transmissions

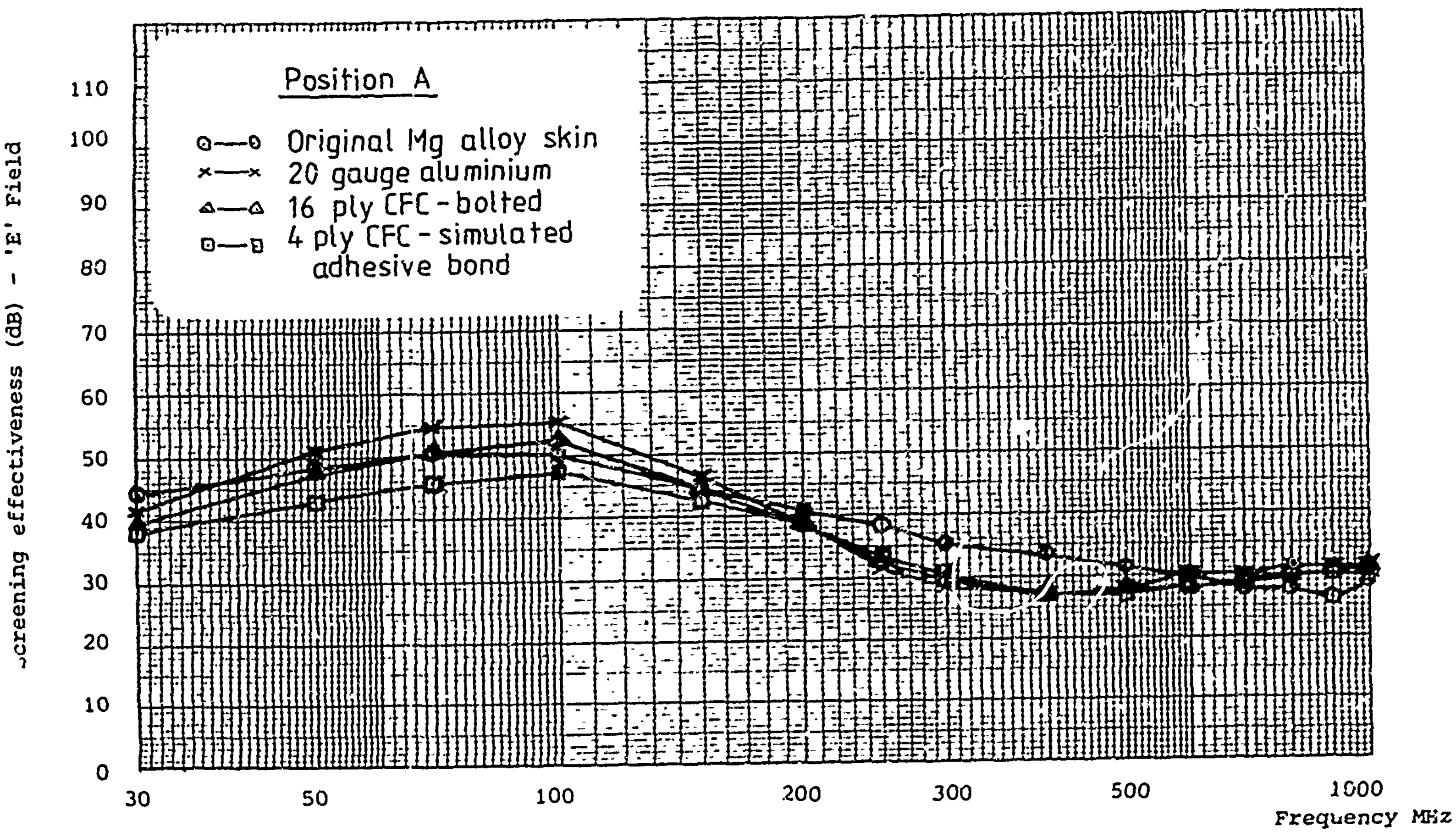


Figure17 Electric screening effectiveness for test panels mounted on the Wessex tail cone

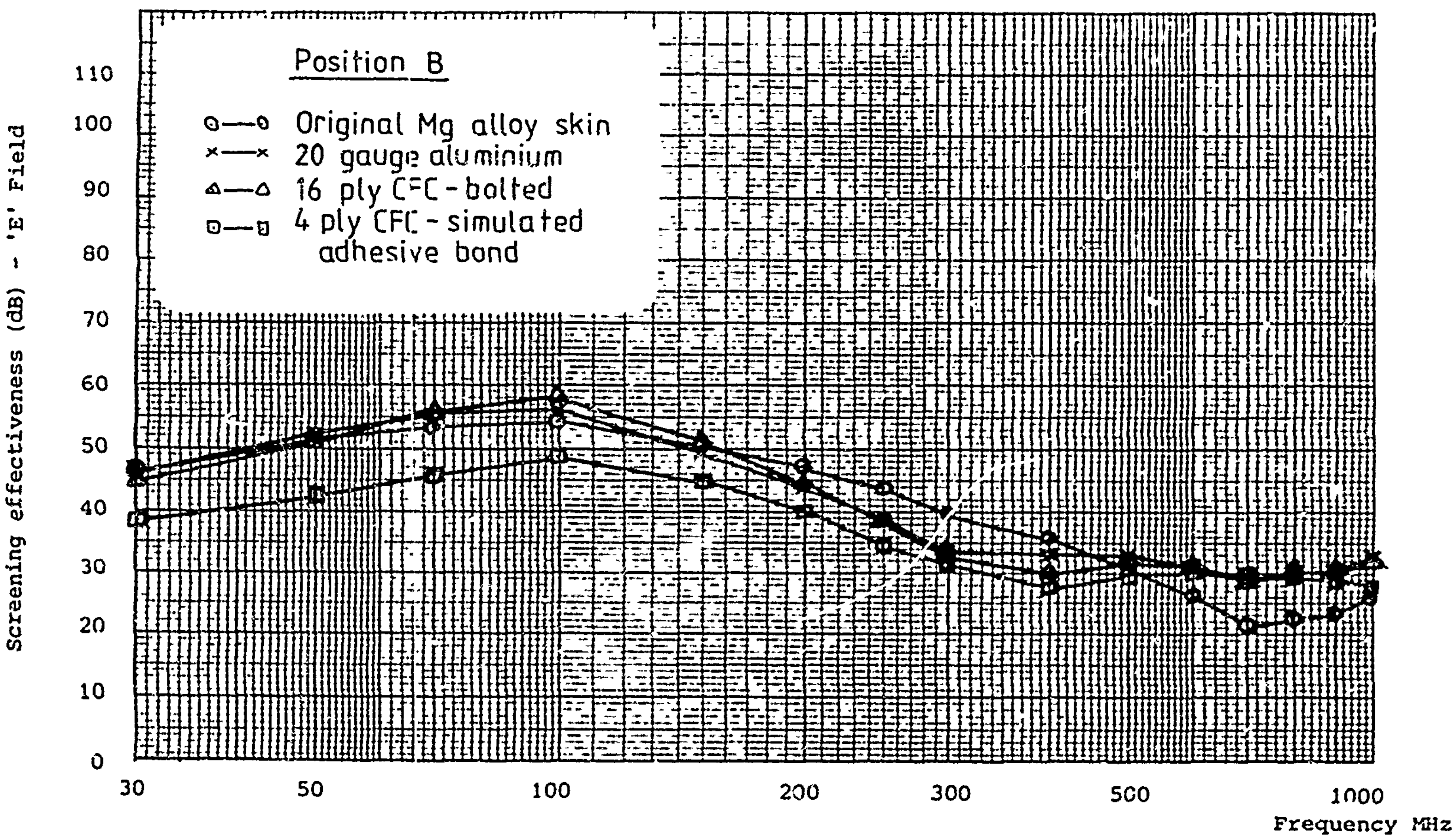


Figure 18 Electric screening effectiveness for test panels mounted on the Wessex tail cone

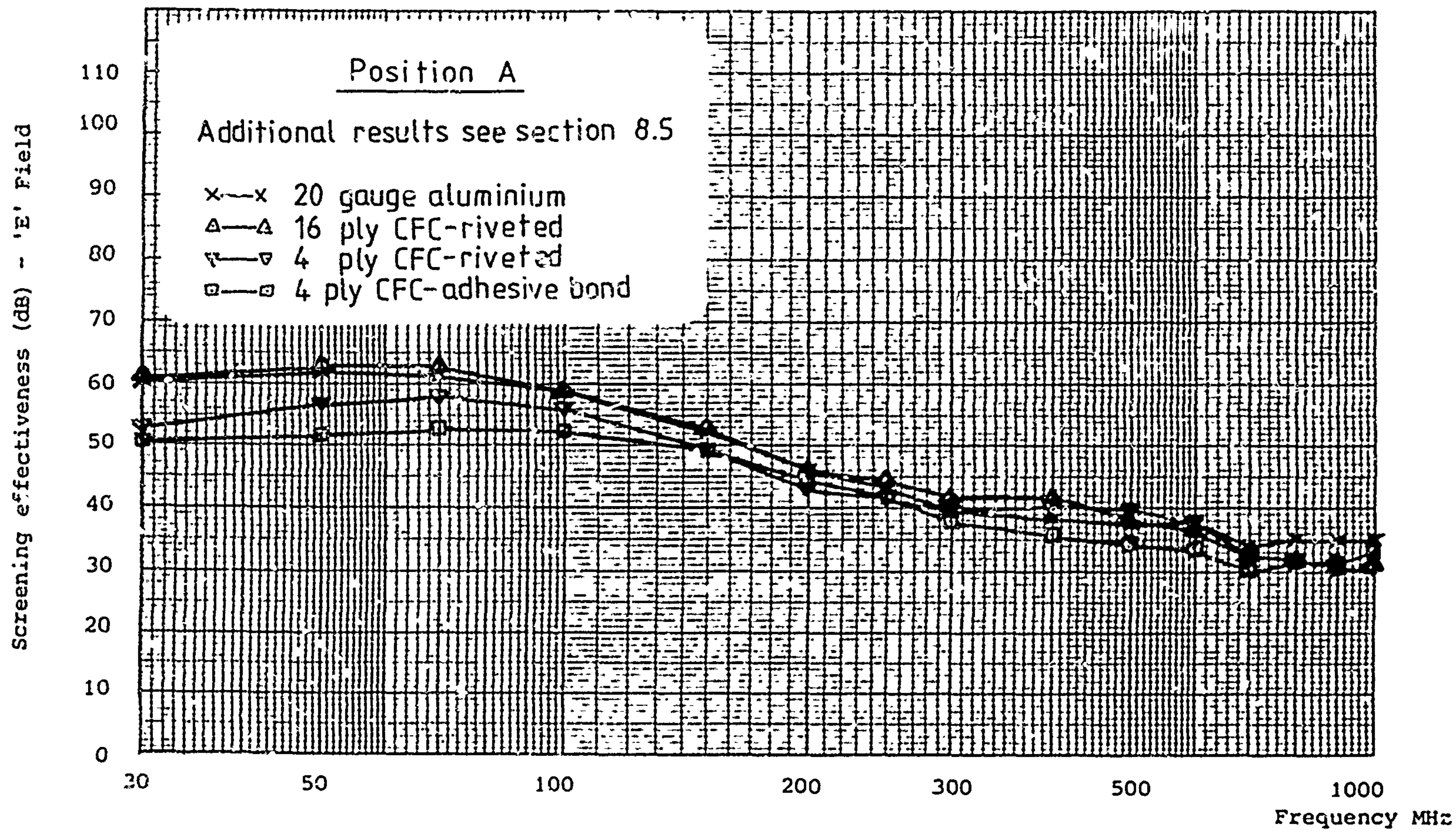


Figure19 Electric screening effectiveness for test panels mounted on the Wessex tail cone

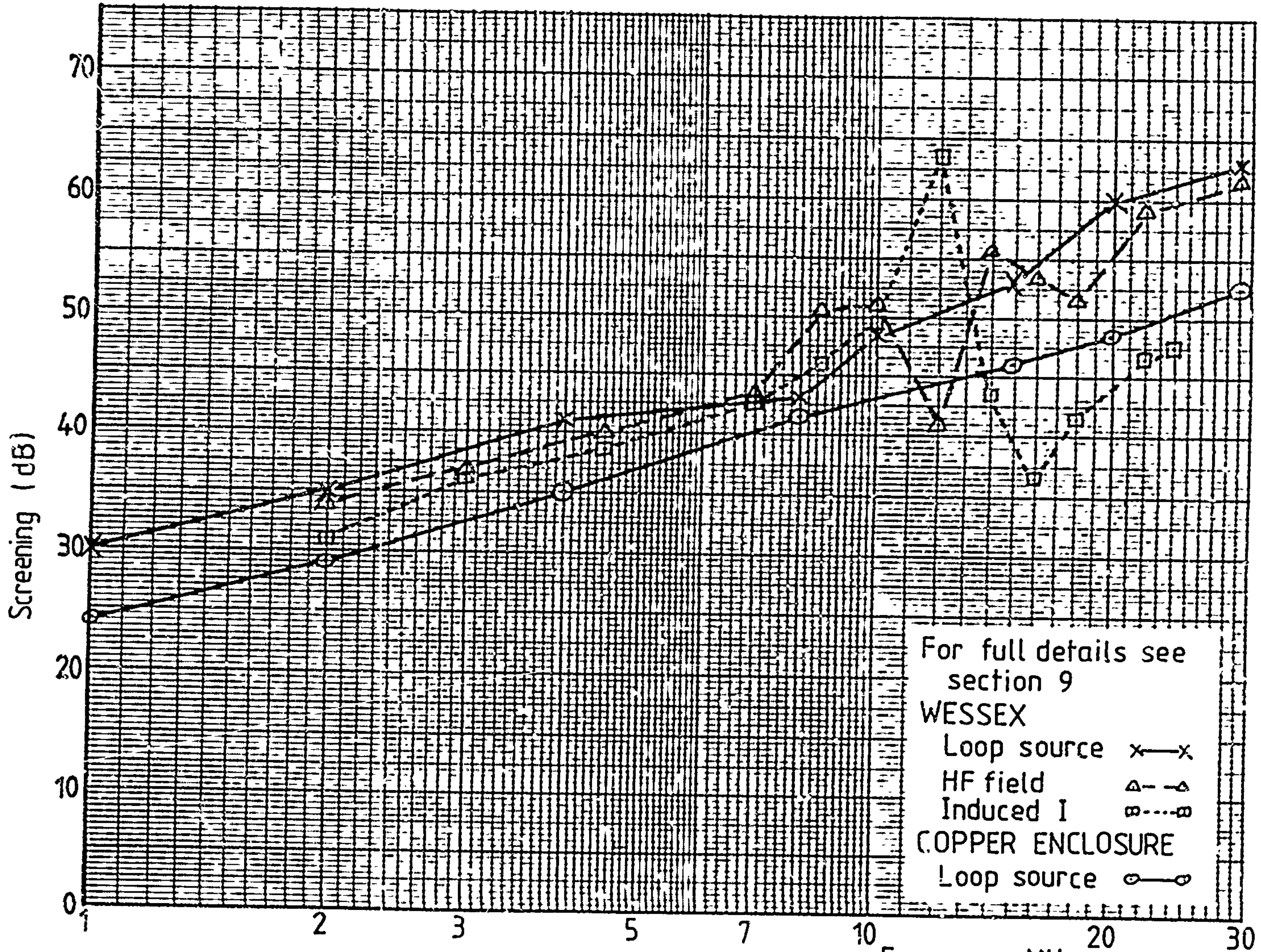


Figure 20 Comparison of screening results for 4 ply riveted/bolted panels

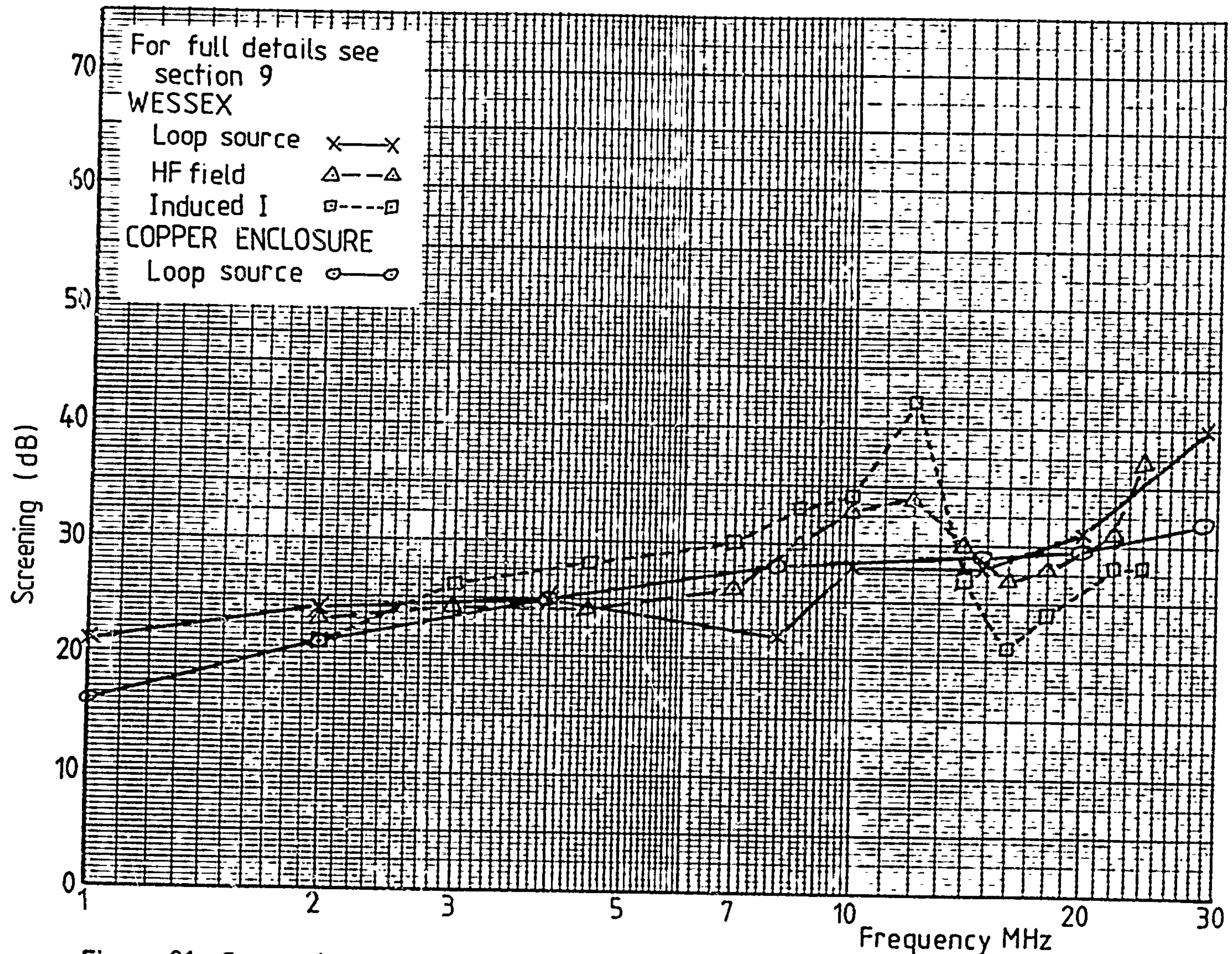


Figure 21 Comparison of screening results for 4 ply adhesively bonded panels

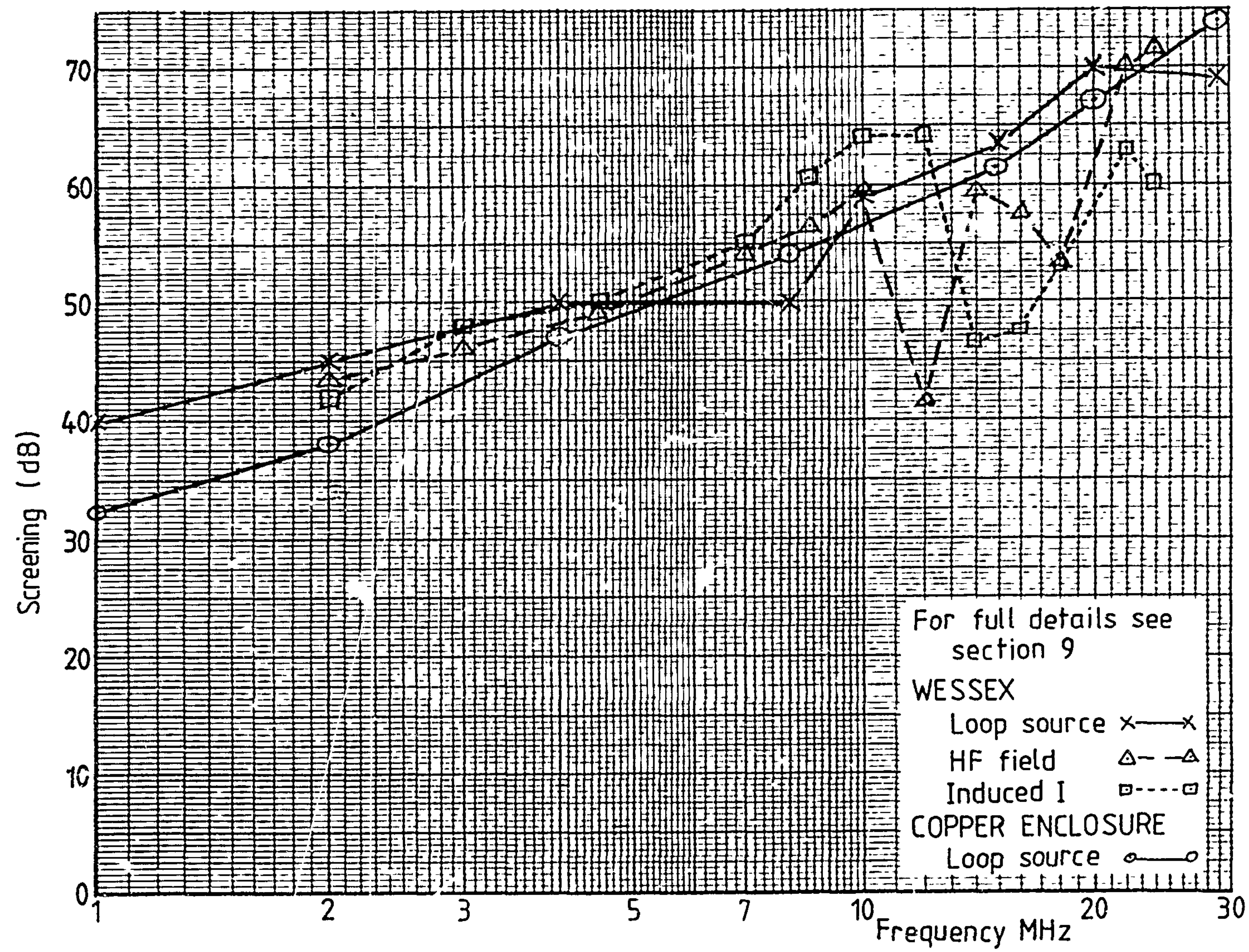


Figure 22 Comparison of screening results for 16 ply riveted/bolted panels

CHAPTER 8

THE SCREENING EFFECTIVENESS OF
A CARBON FIBRE COMPOSITE CYLINDER

A McHale

SUMMARY

The magnetic screening effectiveness of a cylinder constructed from carbon fibre composite material was measured in the frequency range 0.15-30 MHz. Results obtained using both near and distant signal sources were in good agreement with each other and were within 12 dB of screening values obtained by calculation using the d.c. resistivity value measured for the CFC material.

Screening increased approximately linearly with frequency from 20 dB at 0.175 MHz, a value 35-40 dB less than measured for an aluminium cylinder of similar dimensions, up to 70 dB at 30 MHz, which was comparable to the aluminium result.

Insulated joints, introduced into the structure of the CFC cylinder, reduced the screening to less than 20 dB over most of the frequency range.

CONTENTS

1 INTRODUCTION

Previous investigations included measurements of the screening effectiveness of carbon fibre composite (CFC) materials by incorporating flat samples of CFC as part of an otherwise all metal structure.

Results were initially obtained by incorporating CFC samples as part or the whole of one face of a 1 m^3 copper enclosure (Chapters 4 and 5). Further measurements involved the replacement with CFC of one surface panel section in the tail cone of a Wessex HAS Mk 1 helicopter (Chapter 7).

The third and final phase in the present measurement programme is described in this chapter. A cylindrical structure was assembled by bolting together two semi-cylindrical sections of CFC. Magnetic screening effectiveness of this cylinder was determined using the following electromagnetic sources:

(a) A simple near field source - a 0.25 m diameter loop at a distance of 1 m and 2 m(over the frequency range 0.15-30 MHz).

(b) A complex near field source - the Wessex helicopter's hf system at a distance of 5 m (2-24 MHz).

(c) Far field (plane wave) sources - various distant broadcast stations (0.2-12 MHz).

In all the investigations, comparison has been made between the results for the CFC cylinder and those obtained for an aluminium cylinder of simiiar dimensions.

2 DESCRIPTION OF TEST CYLINDERS

2.1 CFC cylinder

The CFC cylinder was manufactured by Structures Department at the Royal Aircraft Establishment, Farnborough. It was originally intended that the body of the cylinder would be manufactured in one piece. This method, however, was not practicable without extensive research into mould techniques. Two semi-cylindrical sections together with two backing strips were therefore manufactured and these were assembled into a cylinder 1.72 m long by 1.0 m diameter. These sections were all

manufactured using XAS fibre and BSL 914 resin with a 16 ply lay-up of 0°, 90° relative to the cylinder axis. Two flat panels, of the same material, with an 18 ply 0° ± 60° lay-up were also supplied for use as end caps.

Figure 1 shows the general assembly of the complete cylinder. The two halves were drilled and countersunk from outside and were butt-jointed by bolting to the backing strips. 5 mm diameter titanium bolts with a countersunk angle of 100° and cadmium plated steel nuts were used to join these sections.

Copper bonding straps were included between every fourth bolt pair on both joints to reduce the impedance across the joint in order to simulate, as far as possible, a jointless CFC cylindrical structure (see Fig.1).

The end caps were attached to copper brackets bolted to the cylinder edges with one cap permanently bolted to these brackets. As ready access was required to reach equipment within the cylinder the second cap was clamped to the brackets. Copper bonding strips, bolted to this end cap, ensured electrical continuity between the cap and cylinder.

2.2 Aluminium cylinder

The aluminium cylinder of length 2.4 m and diameter 1.1 m was manufactured from 22 gauge sheet folded on to a wooden support structure. The body of the cylinder contained three longitudinal overlapped seams riveted every 50 mm. One end cap was folded over and bolted to the cylinder body. The other end cap was clamped to copper brackets on the cylinder edge to provide ready access into the cylinder. This cylinder had been in the open for several years prior to its use in this investigation and, as a consequence, the joints had suffered some corrosion.

3 MEASUREMENT TECHNIQUES

The measurement techniques, described below, refer to both the CFC and the aluminium cylinders.

Each cylinder was positioned on wooden supports with its axis horizontal. The screening effectiveness to the magnetic component of the radiated field was determined for three different sources using the following methods.

3.1 0.25 m loop source

Screening measurements using a loop source were made in the frequency range 0.15-30 MHz. The loop source was excited by a RF Power Labs M102L wideband amplifier and an Advance SG200 signal generator. A 6 dB 50 Ω attenuator was included between the amplifier and the loop to protect the amplifier output stage from impedance mismatch.

The detector, a portable 'H' unit, consisting of a 0.25 m diameter loop and a tuned head amplifier was located at the cylinder centre. The detector output was measured using an Ailtech NM 17/27 measuring receiver. The detector, receiver and operator were all inside the cylinder during the tests.

Measurements were made with the loops in co-planar orientation with the axis of each loop parallel to the cylinder axis. The source was excited at each test frequency and the received level measured. Maximum transfer between loops was found to occur, as in previous investigations (Chapters 3 and 7), when the detector was in the same orientation as the source.

The centre-to-centre separation between the loops was 1 m and 2 m during the tests.

The signal transfer between the loops was also measured over an unobstructed path, i.e. well clear of reflecting objects. The screening effectiveness of the cylinder with its side interposed between the source and detector is the ratio of these measurements, i.e:

$$\text{Screening effectiveness} = \frac{\text{Signal transferred over the unobstructed path}}{\text{Signal transferred through the cylinder side}}$$
(for the same loop separation)

Also included are the results of measurements, for the CFC cylinder, after both the source and detector loops had been rotated so that their common plane was horizontal.

3.2 Wessex hf transmitter

The cylinder was positioned with its axis parallel to the Wessex helicopter centre line and near the starboard side of the tail cone. The distance between the starboard hf wire aerial and the cylinder axis was approximately 5 m.

A 0.14 m diameter loop was used with the Ailtech NM 17/27 receiver to measure the magnetic component of the field radiated by the Wessex hf system. The loop was located at the centre of the cylinder and the field measured with the loop positioned successively in three orthogonal orientations. The magnitude of the field was calculated from the vector sum of these three values. The receiver and operator were also contained within the cylinder for the tests.

The cylinder was removed and the field measurements repeated with the loop supported at the same position with respect to the radiating aerial. The screening effectiveness of the cylinder was then calculated as the ratio of the field strength measured with and without the enclosing cylinder in position.

The transmitter was the helicopter's Collins 618T operated in the 'AM' mode without modulation over the frequency range 2-24 MHz.

3.3 Distant broadcast stations

The cylinder was positioned so that the field from each broadcast station impinged perpendicularly on to the side of the cylinder. The field was measured at the cylinder centre using the portable 'H' unit and the NM 17/27 receiver. The field was also measured a few metres clear of the cylinder and other reflecting objects. The screening effectiveness was then calculated as the ratio of these two field measurements.

Signals from a number of British and continental broadcast stations in the frequency range 0.2-12 MHz were used to measure the screening of the CFC cylinder. The higher screening of the aluminium cylinder however precluded measurements at frequencies other than 0.2 and 0.909 MHz (BBC transmitters at Droitwich and Brookmans Park, Hertfordshire, respectively).

4 RESULTS

Results of magnetic screening effectiveness are given for the CFC cylinder, with the end caps and longitudinal joints fully fastened, and also after:

(a) removing one of the end caps
(b) insulating one longitudinal joint
(c) insulating both longitudinal joints

4.1 Complete CFC cylinder

Figure 2 shows the screening effectiveness for the complete CFC cylinder. The results, at frequencies below 15 MHz, show agreement to within 4 dB between the near field results (the loop source at 1 m and 2 m and the more complex Wessex hf aerial at 5 m from the cylinder axis) and the far field results (broadcast stations at various distances between 50 and 500 km). The spread in results increased at frequencies above 15 MHz. The close agreement between the results, particularly below about 20 MHz, confirms the conclusion of previous investigations (Chapter 6) where it was shown that the screening effectiveness was largely independent of the separation between the source of the incident wave and the structure under test.

Two curves are shown in Fig.2 for the Wessex hf system. The lower curve shows the screening result obtained by considering the vector sum of the field measured for the three orthogonal orientations of the loop. The upper curve shows the screening result obtained by considering one orientation only, i.e. the loop axis coincident with the cylinder axis. Below 10 MHz the two results were identical and have been combined in the figure.

Screening calculated using Miedzinski's theory (Ref.18) is also shown in Fig.2. The calculation used the d.c. resistivity measured for the CFC material used in the cylinder construction. For the purpose of the calculation it was assumed that the CFC material was homogeneous. These calculated values were typically 8-12 dB larger than the measured values.

This result is considered reasonable, since the assumption that the material was homogeneous would have tended to enhance the calculated value. In addition, although care was taken to ensure electrical continuity across the longitudinal joints, the existence of the joints may have reduced the electrical integrity of the cylinder when compared to a continuous structure.

4.2 CFC cylinder with one end cap removed

Figure 3 shows the screening measured at the centre of the cylinder both before and after the removal of one end cap. Currents, induced in the CFC by the loop source, flowed mainly around the cylinder circumference.

This current flow, necessary to maintain the screening, was largely undisturbed by the removal of the end cap and, as a consequence, the screening below 8 MHz was unaffected. Above this frequency, however, there was some leakage through the aperture and this limited the screening to 55 ± 3 dB.

Results in Fig.4 refer to screening measured with both loops horizontal (all other measurements had the loops vertical). Screening for the complete cylinder (with loops horizontal) was very similar to the equivalent screening measured with loops vertical (Fig.3). However, the reduction in screening due to the removal of one end cap was more marked for the horizontal loop configuration (Fig.4). Current induced in the cylinder by the horizontal loop source flowed lengthwise and the current path was completed via the end caps. The removal of one end cap interrupted this current path and, as a consequence, the screening for this configuration (Fig.4) was limited to a maximum value of 38 dB, compared with 55 dB for the vertical loop configuration (Fig.3).

4.3 CFC cylinder with one insulated joint

Figure 5 shows the effects of insulating one of the longitudinal joints to simulate the poor electrical bond that could occur if such a joint was adhesively bonded. One line of titanium bolts was replaced with nylon bolts. A layer of masking tape between the backing strip and the cylinder prevented any random contact between exposed carbon fibres at the bolt holes.

Screening was measured using the loop source at 2 m and also the Wessex hf system at 5 m. The cylinder was positioned with the insulated joint adjacent to the sources and also on the opposite side of the cylinder.

The insulated joint greatly reduced the screening integrity of the cylinder throughout the frequency range 0.15-30 MHz. In some instances the screening was more than 40 dB below the values for the complete cylinder with both longitudinal joints conducting. The screening was least when the insulated joint was adjacent to the source.

The cylinder with the insulated joint was also found to give different screening values to fields from the loop and from the Wessex hf system.

This is thought to be due to the different orientations of the two incident wave-fronts relative to the insulated joint in the cylinder.

4.4 CFC cylinder with two insulated joints

Figure 6 shows the screening results for the cylinder with both longitudinal joints insulated in the manner described above and also, for comparison, the results for the complete cylinder. The screening was again greatly reduced by these insulated joints. The results in Fig.6 were measured with the joints positioned one adjacent to and one opposite to the source. The screening was found to be insensitive to the relative positions of the sources and the joints around the cylinder. Other results, not shown, taken with one joint above and one below the cylinder, gave very similar results.

The screening increased from 6 dB at 0.175 MHz to 36 dB at 30 MHz. Over the 2-16 MHz range the screening was essentially constant with a value of about 20 dB.

4.5 Aluminium cylinder

Screening results for the aluminium cylinder are shown in Fig.7. The results for the loop source at 2 m separation were found to rise with increasing frequency at a rate of approximately 10 dB per decade. The other results show less frequency dependence.

The aluminium cylinder gives much greater screening at the lower frequencies than the CFC cylinder (Fig.2). However, CFC screening rises rapidly with frequency, at 20 MHz being comparable with aluminium. Calculation for the aluminium cylinder, assuming a joint-free construction, gives a magnetic screening which exceeds 100 dB at 0.15 MHz and which increases rapidly with frequency. The measured results, 55-75 dB, are considerably lower than those predicted by calculation. It is thought that the weathered riveted joints form impedance discontinuities which greatly reduce the screening to give values below those expected from a consideration of the metal properties alone.

The larger spread in the screening results, 8 dB for the aluminium compared with 4 dB for CFC, is most likely due to a decreased accuracy in the field measurements at the greater screening levels and could be due to the wanted signals inside the cylinder approaching the receiver noise level.

5 CONCLUDING REMARKS

The results obtained in the present series of measurements on a non-continuous carbon fibre composite cylinder confirm in general terms much of the previous work. More specifically, the technique to determine the screening effectiveness of the material by considering separately the magnetic and electric components has yielded consistent results.

The magnetic screening performance of the CFC material is inherently poor, particularly within the hf band, 2-30 MHz, and it is considered that the inclusion of impedance discontinuities by way of panel joints will degrade this performance still further.

Electric screening performance was not measured in this investigation. However, from previous work (Chapters 3 and 4) the complete cylinder can be expected to yield electric screening results in excess of 60 dB between 30 MHz and 1000 MHz. Some reduction in screening is likely at the higher frequencies due to leakage through the thin slot-like apertures that exist between fixing points at the end caps. The inclusion of insulated longitudinal joints may also reduce the screening in the 30-1000 MHz range to about 50 dB.

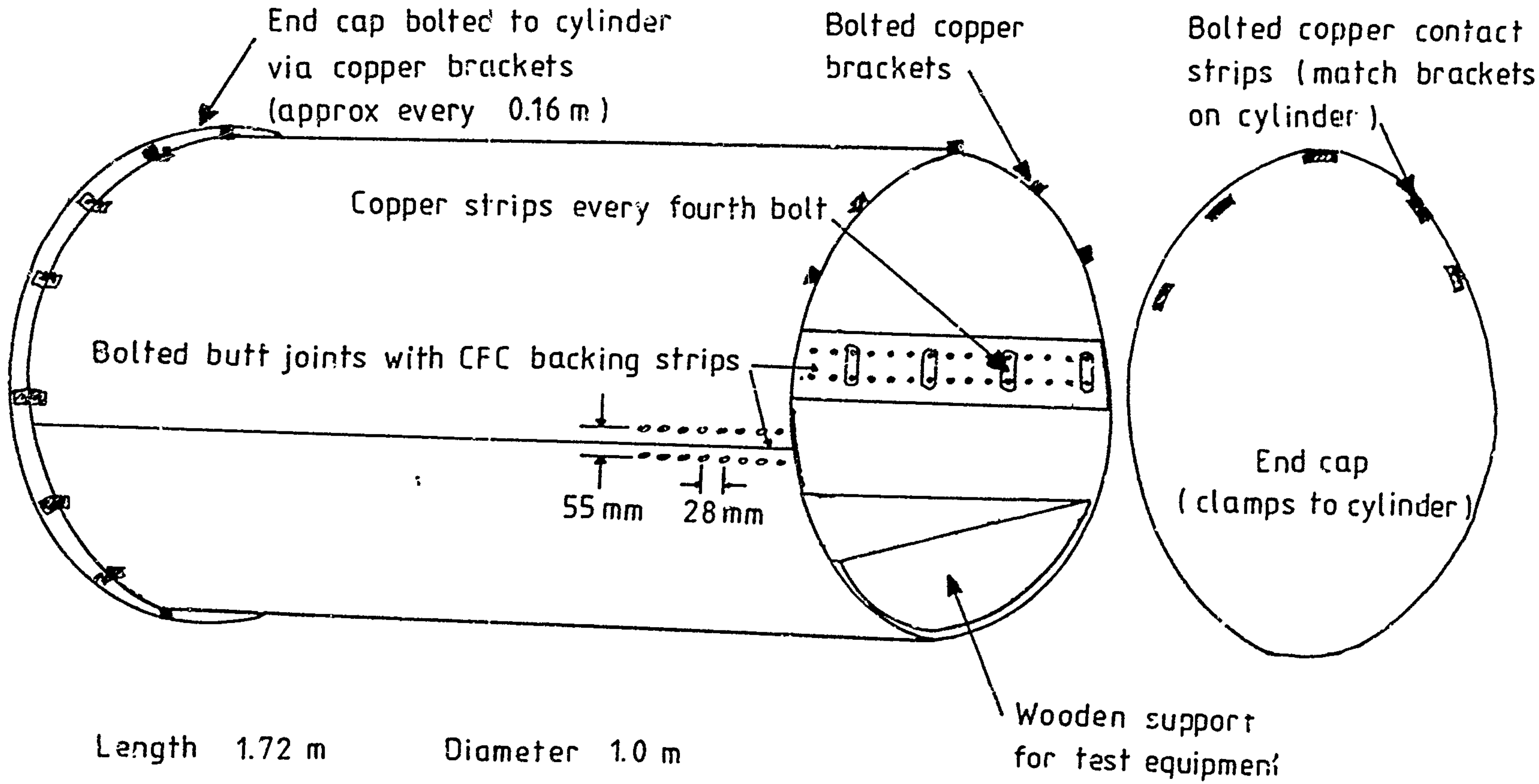


Figure 1 General assembly of CFC cylinder

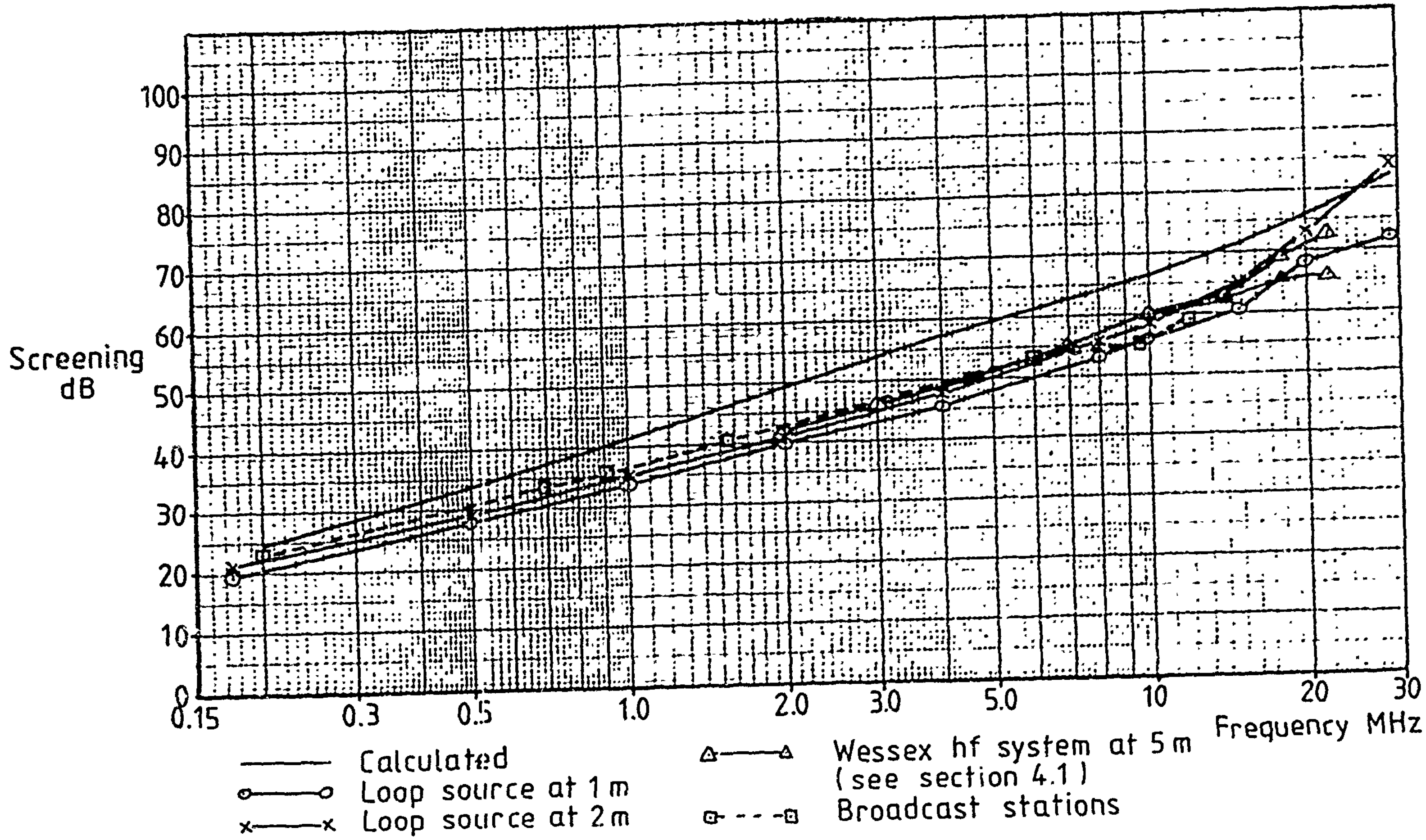


Figure 2 Magnetic screening effectiveness of CFC cylinder

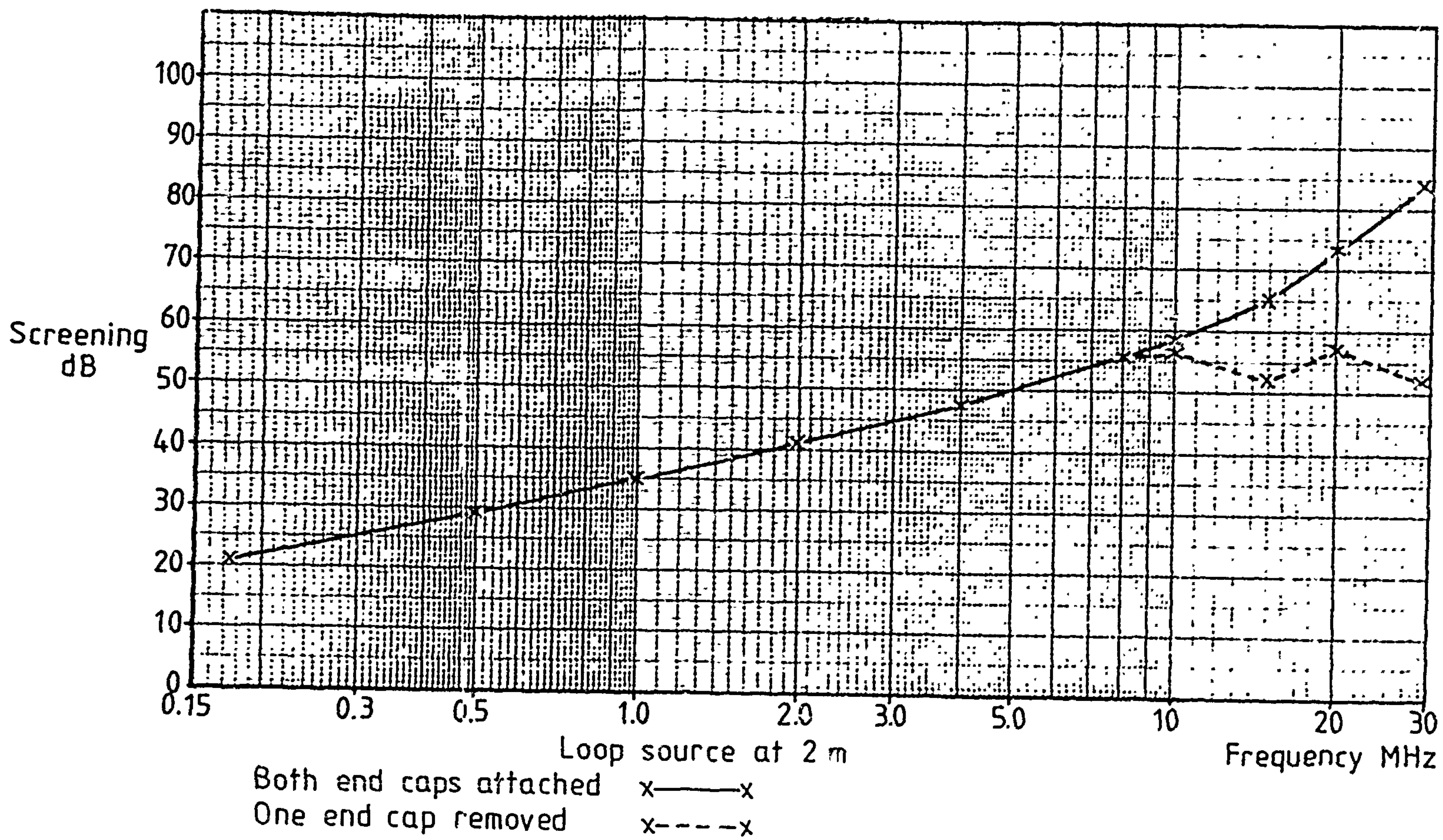


Figure 3 Magnetic screening effectiveness of CFC cylinder with one end cap removed

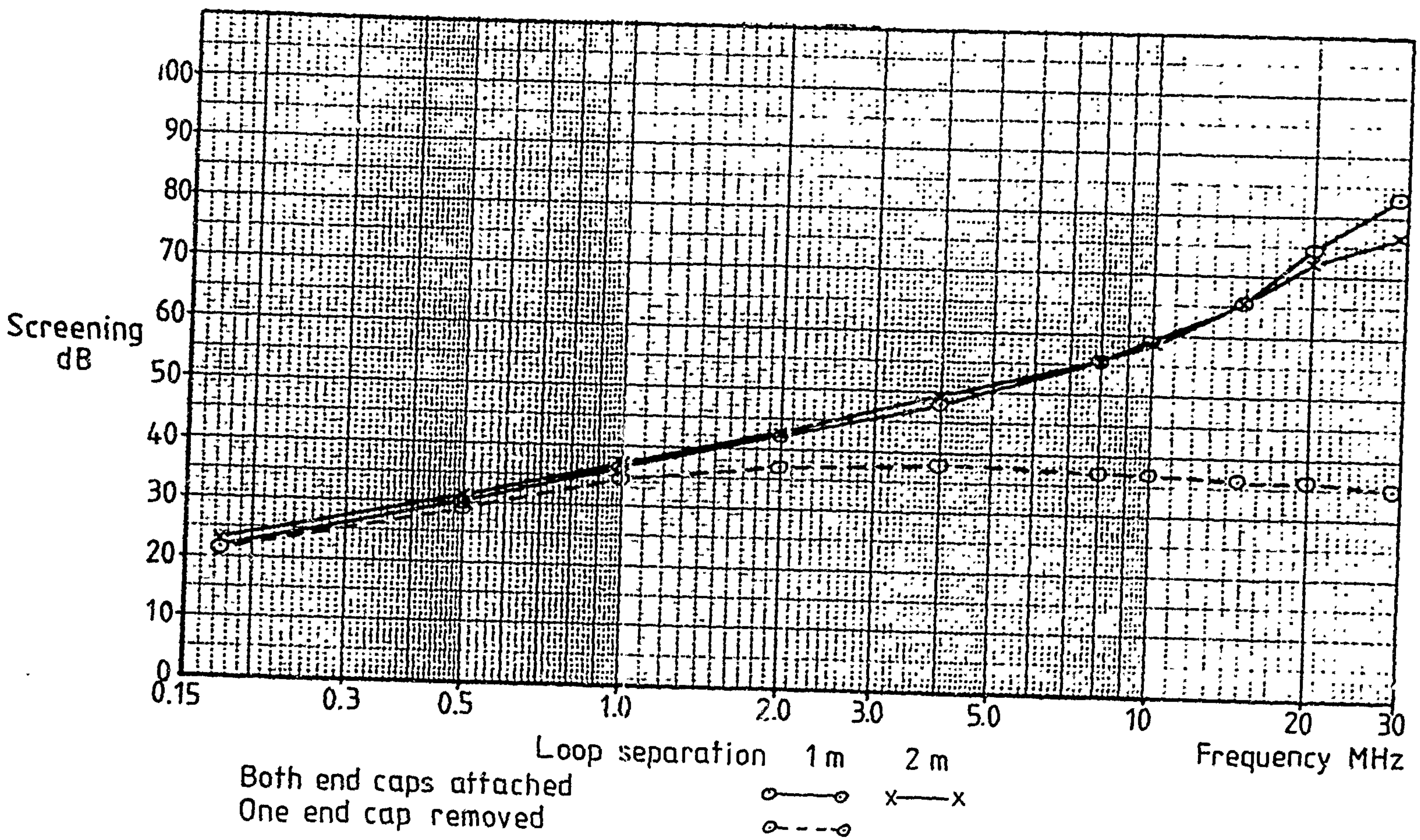


Figure 4 Magnetic screening effectiveness of CFC cylinder measured using horizontal loop source and detector

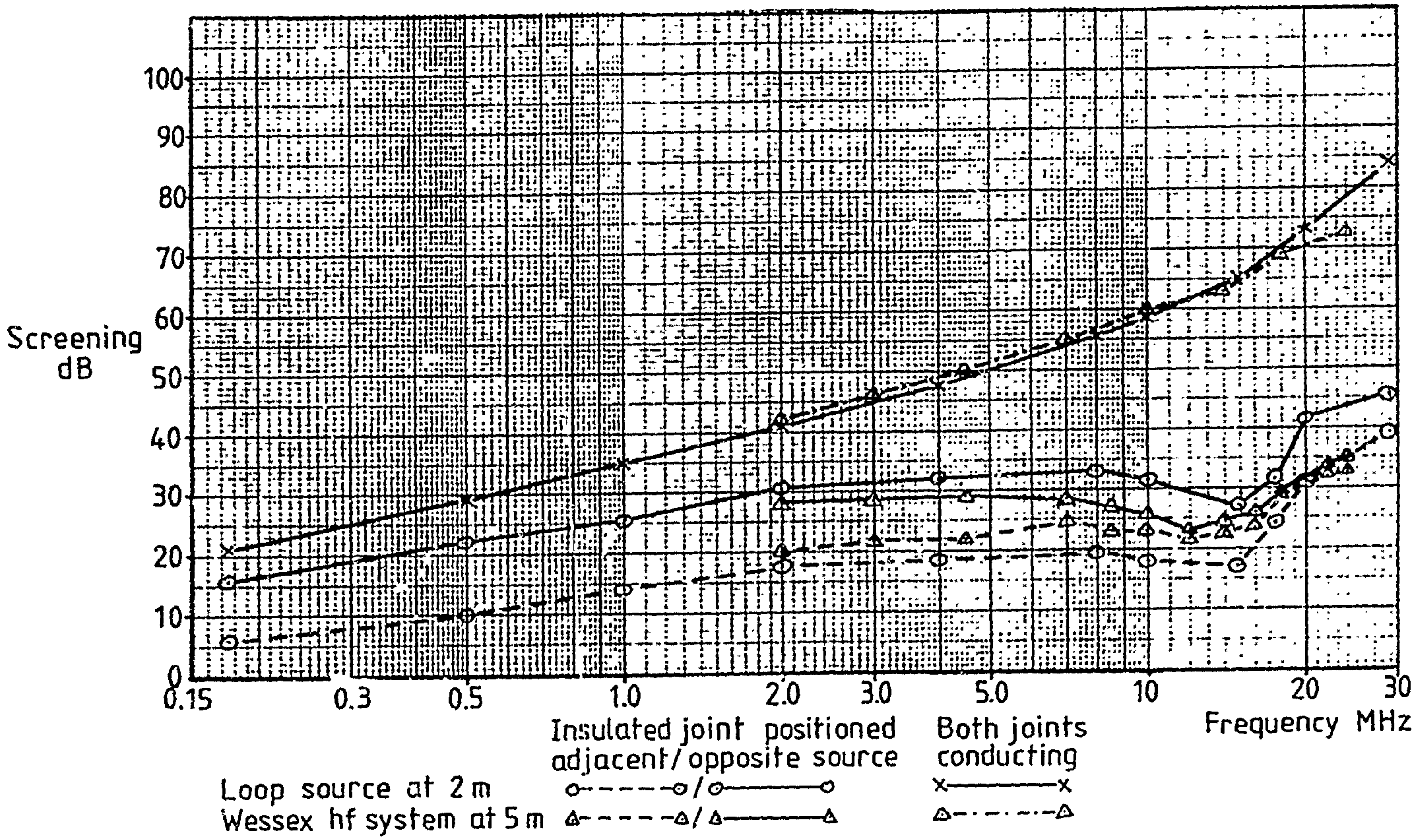


Figure 5 Magnetic screening effectiveness of CFC cylinder with one insulated joint

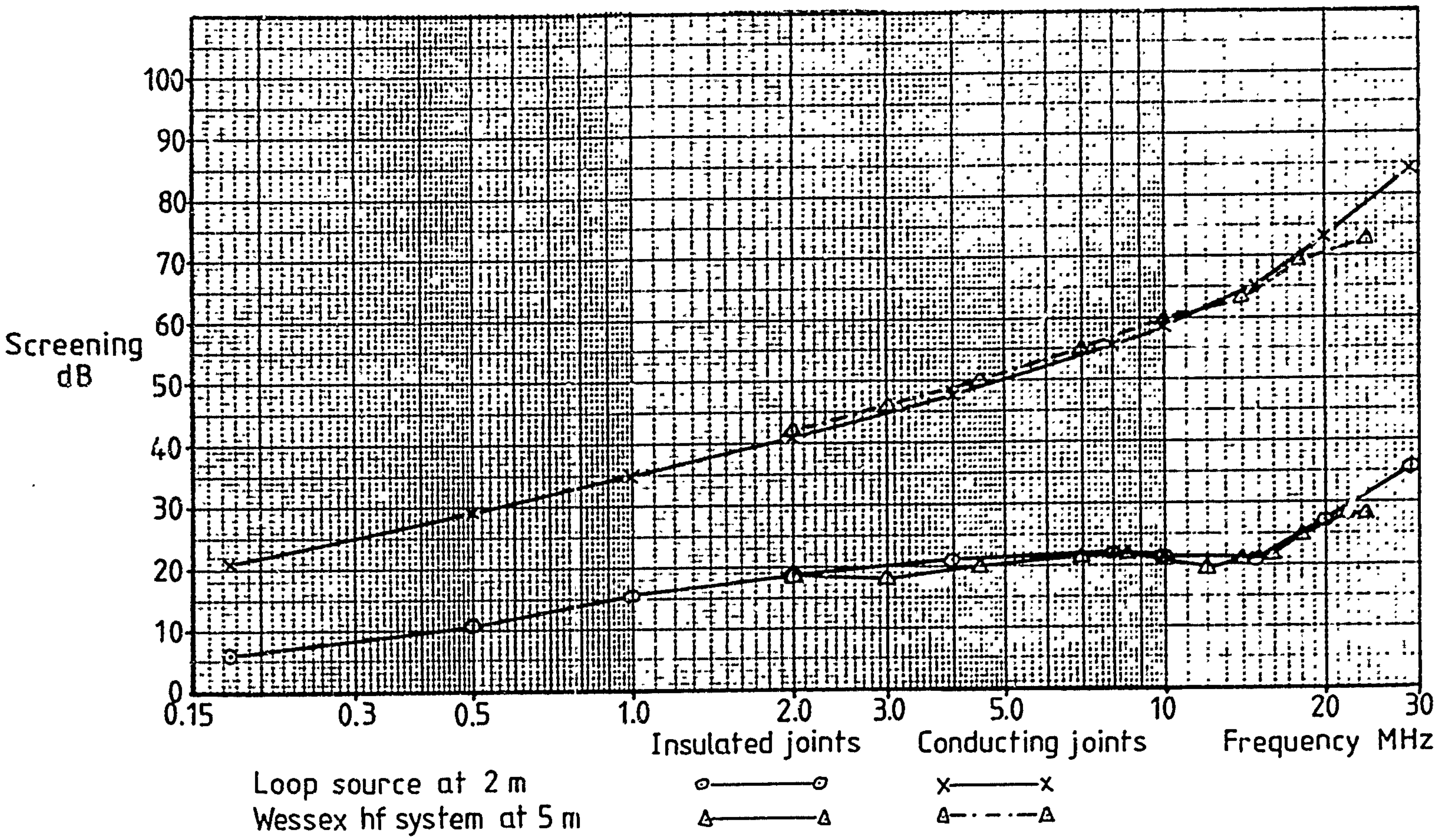


Figure 6 Magnetic screening effectiveness of CFC cylinder with two insulated joints

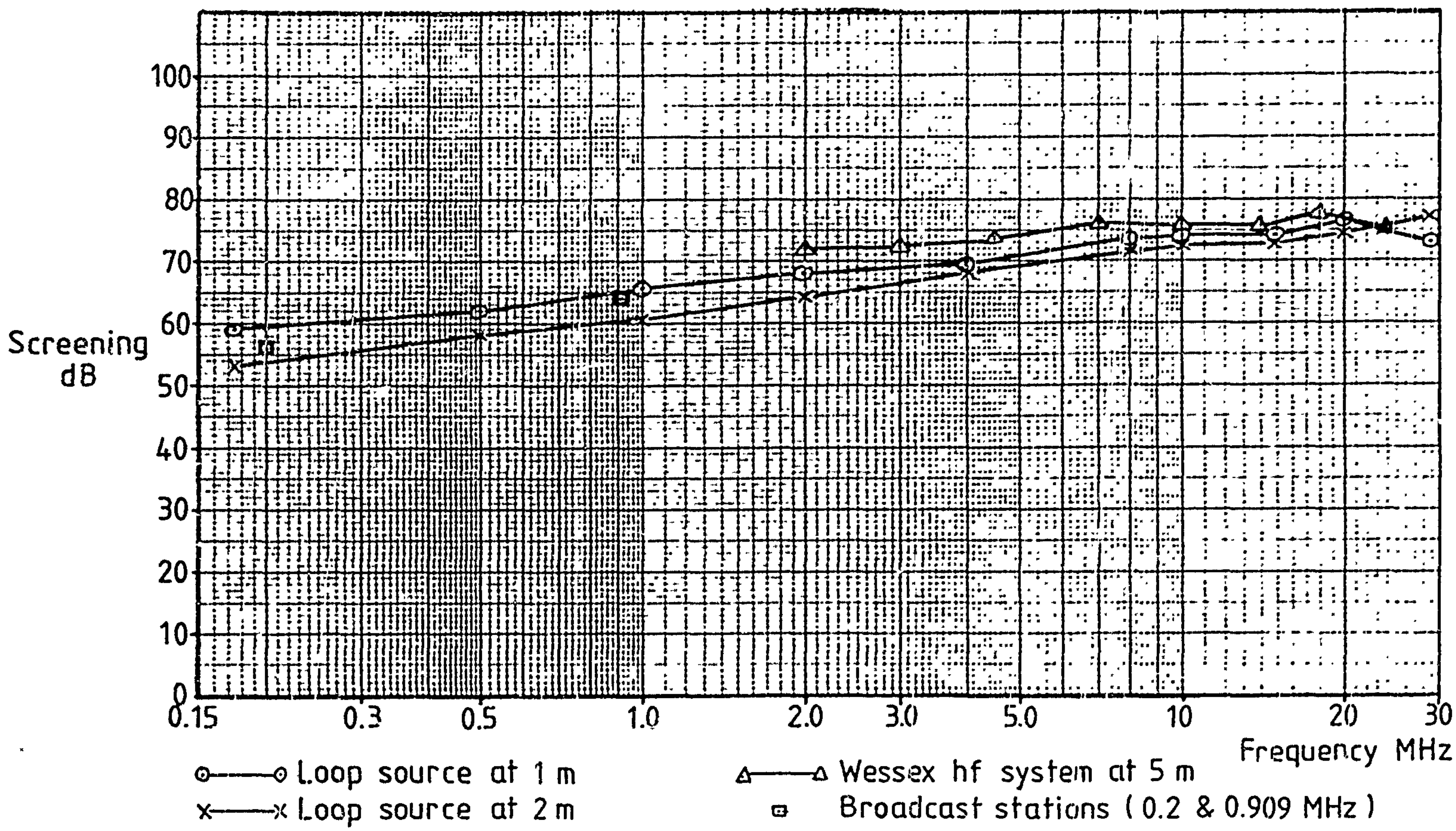


Figure 7 Magnetic screening effectiveness of aluminium cylinder

CHAPTER 9

THE PERFORMANCE OF VHF AND UHF AERIALS MOUNTED ON CARBON FIBRE COMPOSITE MATERIALS

A McHale

SUMMARY

Aerial isolation, VSWR and radiation pattern measurements were compared for vhf and uhf aerials mounted on CFC and aluminium cylinders. There was generally little difference between the CFC and aluminium installations although within the vhf aircraft communications band, 118-136 MHz, the results for the CFC cylinder indicated a greater VSWR and a less uniform azimuthal radiation pattern.

One original panel section of a Wessex helicopter tail cone was replaced with carbon fibre composite material. Aerial isolation was measured between 'standard fit' aerials on the helicopter and an aerial first mounted on the original panel and then on the replacement CFC and aluminium panels. No differences were found in the aerial isolation results other than those caused by changes in the tail cone contour.

CONTENTS

1 INTRODUCTION

As part of the overall investigation into the rf properties of carbon fibre composite materials, the following aspects of aerial performance at vhf and uhf were investigated for selected aerials mounted on a 1 m diameter x 1.72 m CFC cylinder.

(a) Aerial isolation for quarter-wave resonant monopoles in the frequency range 118-1000 MHz

(b) VSWR of typical vhf and uhf aircraft communications aerials

(c) Radiation patterns (in azimuth) for typical vhf and uhf aircraft communications aerials

In all these investigations, comparison has been made between the results for the CFC cylinder and those obtained for an aluminium cylinder (1.1 m diameter x 2.4 m). In addition, aerial isolation in the frequency range 30-1000 MHz was measured between aerials mounted on a Wessex helicopter airframe. This ground-experimental vehicle had been modified by replacing with carbon fibre composite (CFC) most of one metal panel on the starboard side of the tail cone, a section some 2 m long x 0.6 m high.

Aerial isolation was measured between aerials mounted in turn on the original fuselage and on the CFC and aluminium test panels, and other selected aerials on the helicopter.

2 MEASUREMENT TECHNIQUES

2.1 CFC cylinder

Full details of the construction of the CFC and aluminium cylinders are found in Chapter 8.

2.1.1 Aerial isolation

Within the frequency range 118-1000 MHz, aerial isolation was measured between a pair of brass monopoles mounted midway along the cylinder and at various angular separations around the cylinder circumference. The cylinder was supported 1 m above ground with its axis vertical to the ground to reduce the effects of ground reflection (Fig.1).

A signal was applied to one aerial and the level received by the second aerial was measured (X dB). The signal level received by connecting the signal generator directly to the receiver via the same cables as fed the transmit and receive aerials was also measured (Y dB). The aerial isolation is given by (Y-X)dB .

A series of different length monopoles was used. These were chosen to be quarter-wave resonant at each test frequency.

2.1.2 Voltage standing wave ratio

The VSWR was measured for each aerial mounted midway along the cylinder. A Merrimac CR20-215 directional coupler was connected to the base of the aerial and the ratio of forward power to reflected power was measured throughout the operational frequency range of the aerial. The VSWR was derived from this ratio.

The aerials tested were a Chelton 21-4B vhf monopole and a Chelton 16-11-P1 uhf blade. The vhf monopole was mounted both perpendicularly and also at 30° from the perpendicular, slanting along the cylinder.

2.1.3 Radiation patterns

The cylinder was positioned with its axis horizontal on a turntable (Fig.2). The aerial under test was centrally mounted on top of the cylinder and was approximately 2 m above the ground.

A 30-300 MHz biconical aerial was set up 30 m from the cylinder, vertically polarised and at a height of 4 m above ground, to measure the field strength radiated from the cylinder-mounted aerial. Allowing for the slope of the ground, the angle of radiation towards the receiving aerial was about 2° above horizontal.

The cylinder was rotated using the turntable and the field strength radiated by the test aerial was measured at the receiving site. Radiation patterns were obtained, essentially in azimuth, for the Chelton 21-4B and 16-11-P1 aerials. The 21-4B was fixed to the cylinder using both the perpendicular and slant mounting options.

2.2 Aerial isolation on Wessex helicopter

Full details of the CFC test panels and the modifications to the helicopter tail cone panels are given in Chapter 7.

Figure 3 defines the aerial isolation and method of measurement. A frequency range of 30-1000 MHz was used, thus covering both in-band and out-of-band conditions for the aerials under consideration. Figure 4 shows the position of the test panel and aerials. Two aerials were used : a Chelton 16-11-P1 uhf blade and a Chelton 21-4B vhf monopole. Each was mounted in turn at the centre of the test panel. Isolation was then measured between the helicopter's original upper and lower uhf communications aerials and the test aerials.

3 RESULTS

3.1 CFC cylinder

3.1.1 Aerial isolation

Figure 5 shows the aerial isolation for quarter-wave monopole aerials mounted on the CFC and aluminium cylinders. Values calculated using empirical formulas (Ref. 19) are also shown. The measured and calculated results indicate that in general, the empirical formulas work equally well for aerials mounted on both CFC and aluminium structures.

Two calculated curves are shown for the 90° aerial separation. These are based on the formulas for isolation over both a plane surface and a curved surface. The 90° separation for the 1 m diameter cylinder is an intermediate condition, in that the aerials are partly obscured from each other. The plane surface formula is preferred in this case as it gives the lower isolation, erring on the safe side.

The larger excursions in the measured values for the 180° separation are indicative of interference effects due to multipath propagation around the cylinder.

At frequencies of 118 MHz and 136 MHz (the vhf aircraft communications band) isolation for aerials mounted on the CFC cylinder was higher than expected from consideration of the results of the calculations and the aluminium cylinder measurements. This result is in agreement with the

radiation pattern tests, Section 3.1.3, where the radiation from the aerial was at a minimum at azimuthal angles of ±90° relative to the cylinder axis and was less, at these angles, when mounted on CFC than when mounted on aluminium.

3.1.2 Voltage standing wave ratio

Figure 6 compares the VSWR results for the CFC and aluminium cylinders. The VSWR for the 21-4B vhf monopole was higher when mounted on the CFC. The CFC values were, however, still within the manufacturer's specification (2.25 : 1 for normal mounting and 2.5 : 1 for slant mounting; frequency range 118-156 MHz) except for the normal mounting where the limit was marginally exceeded above 153 MHz.

The surface resin of the CFC was removed by abrasion to ensure a good electrical contact between the aerial base and the carbon fibres and the measurement repeated with the 21-4B aerial slant mounted. A marginal improvement was obtained. This result is not unexpected as the coupling between the aerial flange and the CFC is mainly capacitive.

The VSWR results for the 16-11-P1 uhf blade indicate little difference between mounting the aerial on the CFC and on the aluminium cylinders.

3.1.3 Radiation patterns

The results of radiation pattern measurements for the Chelton 21-4B vhf monopole are shown for three fixed frequencies in Figs.7-9. The radiation pattern was the least uniform at 118 MHz (Fig.7). Field strength measured for the aerial mounted on any of the two cylinders was of similar mean value but there was greater variation in the radiation pattern for the aerial mounted on the CFC cylinder. Also, there was a worsening of the radiation pattern for the CFC at 118 MHz after the surface resin at the aerial base had been removed to improve the electrical bond between the carbon fibre and the aerial. At other frequencies the removal of the resin had little effect on the radiation pattern. Maximum variations in the radiation pattern were 12 dB for CFC and 6.5 dB for aluminium.

The minimum in the radiation pattern which occurred to the sides of the CFC cylinder (and to a lesser extent the aluminium cylinder) particularly

at 118 MHz, is thought to account for the greater than predicted aerial isolation measured at the vhf frequencies (see Fig.5).

Figure 10 compares the radiation patterns for the Chelton 16-11-P1 uhf blade when mounted on the two cylinders. The two field strengths were similar and showed no more than 2 dB variation in the radiation pattern.

3.2 Aerial isolation on Wessex helicopter

Figure 11 compares the aerial isolation results for the Chelton 16-11-P1 uhf blade aerial when mounted on each of the three panels and also at the same position on the original magnesium alloy skin (i.e. before the modification to install the test panels). No significant differences were noted between results for the three test panels.

There were however differences of up to 10 dB between results obtained using the original fuselage to those using the modified fuselage incorporating the test panels. Isolation for the aerial mounted on the test panels was up to 10 dB lower to the uhf upper aerial and 10 dB higher to the uhf lower aerial than when mounted on the original fuselage skin. These differences are due to the change of surface contour of the tail cone caused by the incorporation of the flat test panels.

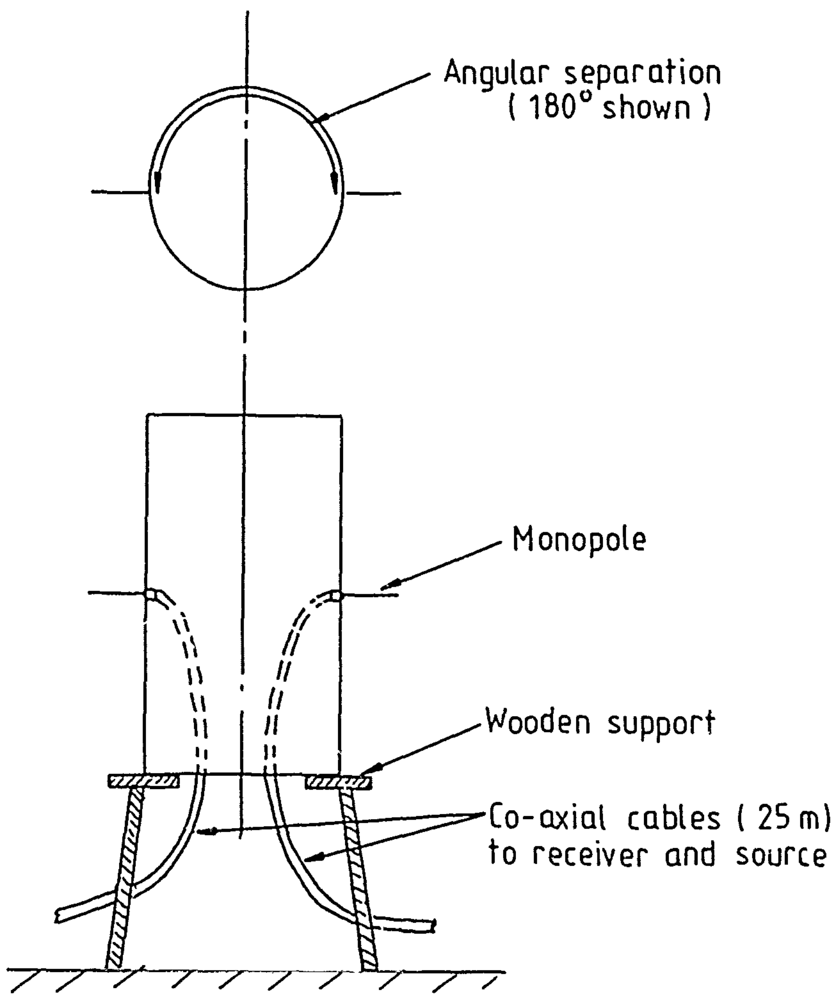
Figure 12 compares results for the Chelton 21-4B vhf monopole when mounted on 20 gauge aluminium and on 4 ply adhesively bonded CFC. No significant differences were noted between results for these two test panels.

4 CONCLUDING REMARKS

There was generally little difference between the CFC and aluminium cylinder installations, although within the vhf aircraft communication band, 118-136 MHz, the results for the CFC cylinder indicated a greater VSWR and a less uniform azimuthal radiation pattern. These differences, however, may be due to the unequal sizes of the two cylinders.

Within the bands 118-136 MHz and 225-400 MHz the results indicate that aerial performance should not be significantly degraded by using CFC material but caution may be necessary if the CFC is painted or environmentally protected prior to aerial installation.

Results of aerial isolation measurements on the Wessex airframe were not dependent on the type of groundplane (CFC or metal) and the only differences noted were due to changes in the tail cone contour.



Received level via monopoles = X dB
Received level direct (via same cables) = Y dB

Aerial isolation = (Y - X) dB

Figure 1 Configuration for aerial isolation measurements on CFC and aluminium cylinders

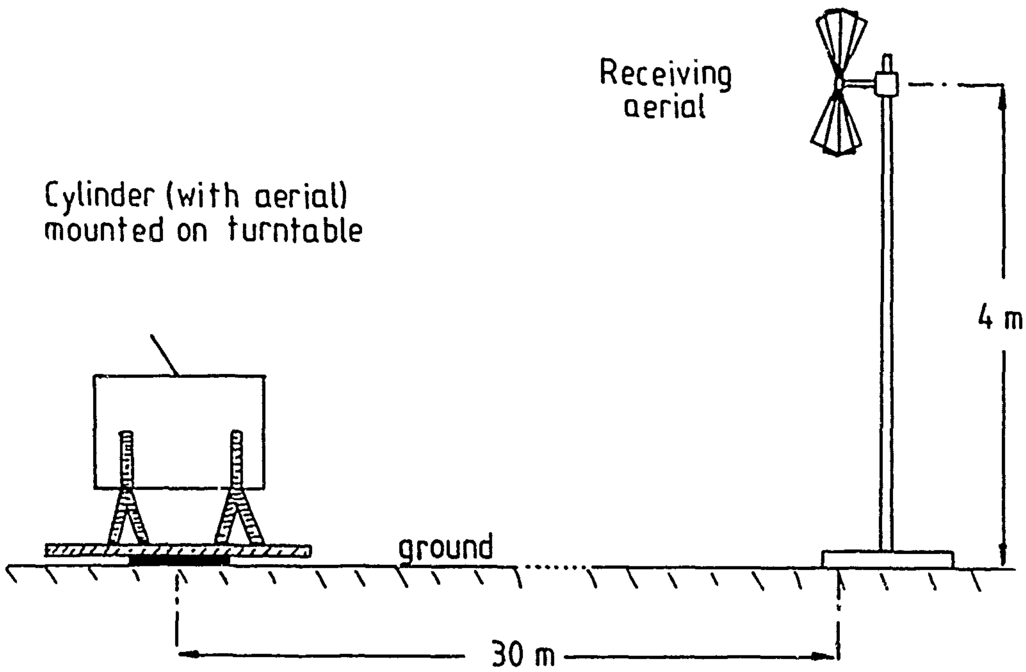


Figure 2 Configuration for radiation pattern measurements

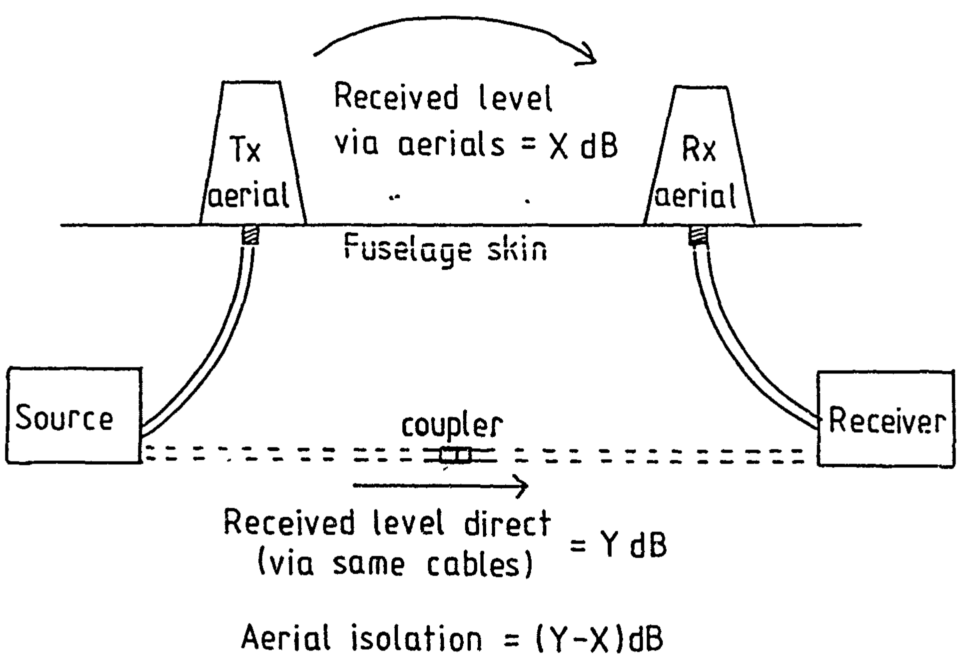


Figure 3 Configuration for aerial isolation measurements on Wessex helicopter

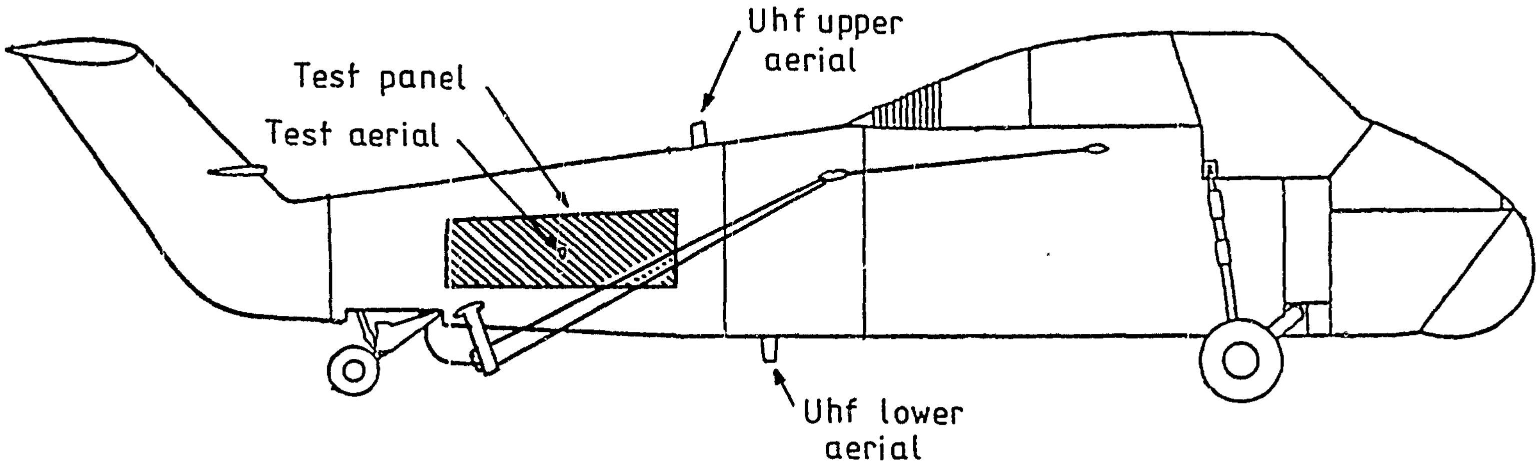


Figure 4 Test panel and aerial positions

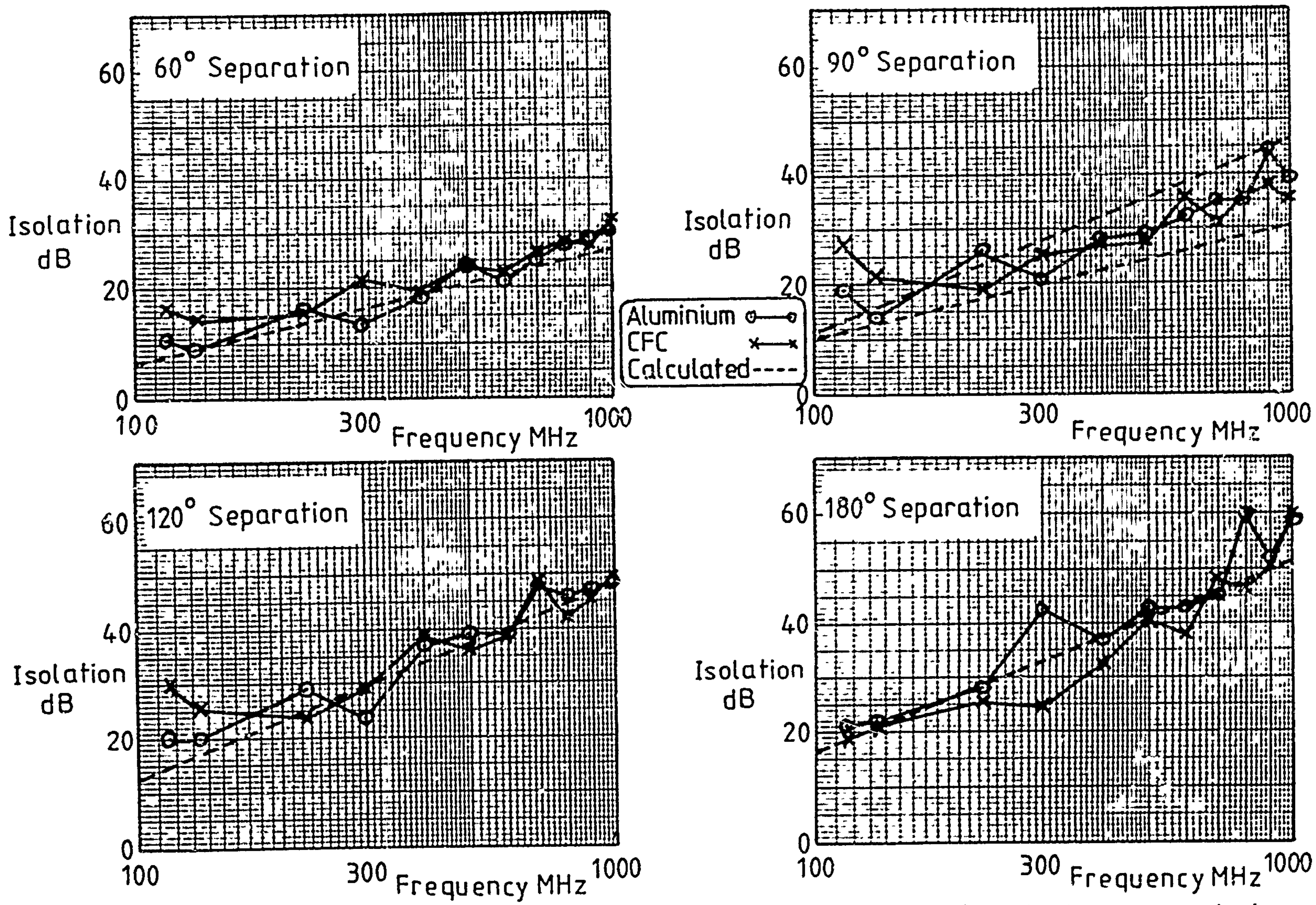
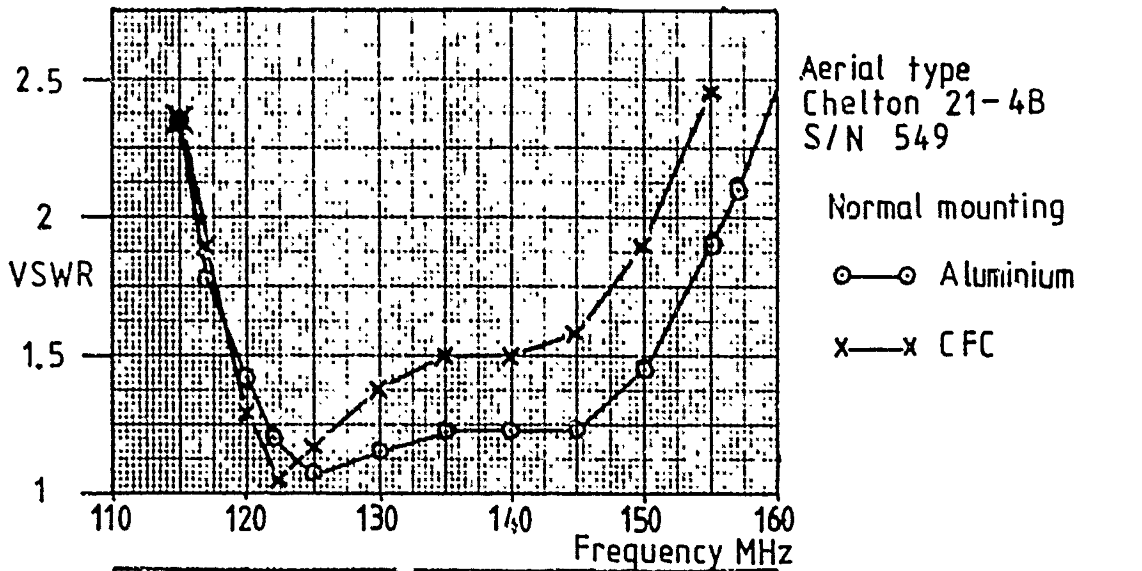
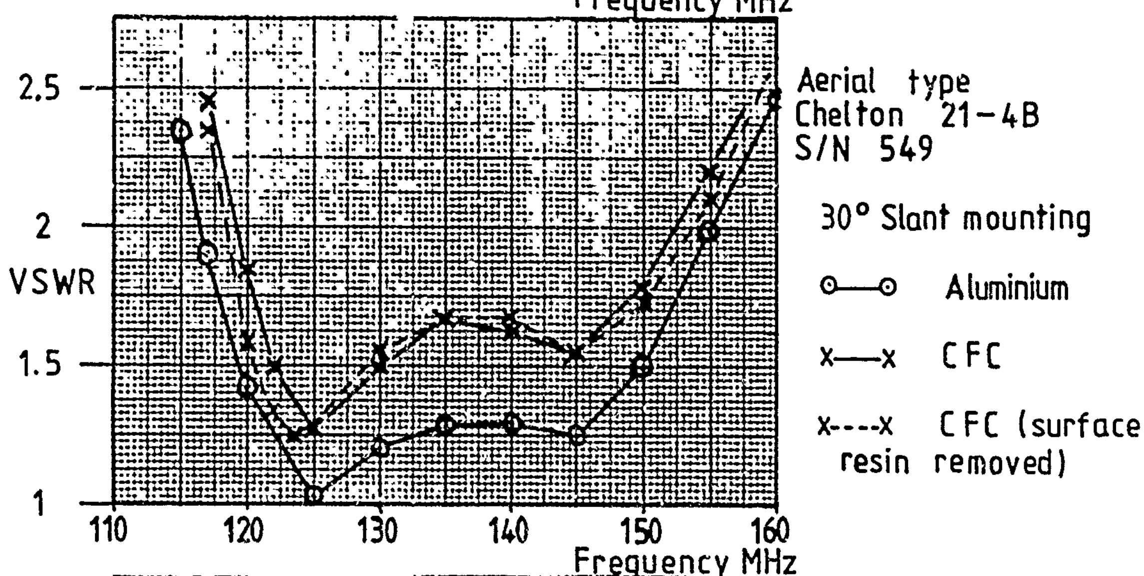


Figure 5 Comparison of aerial isolation for λ/4 monopoles mounted on CFC and aluminium cylinders





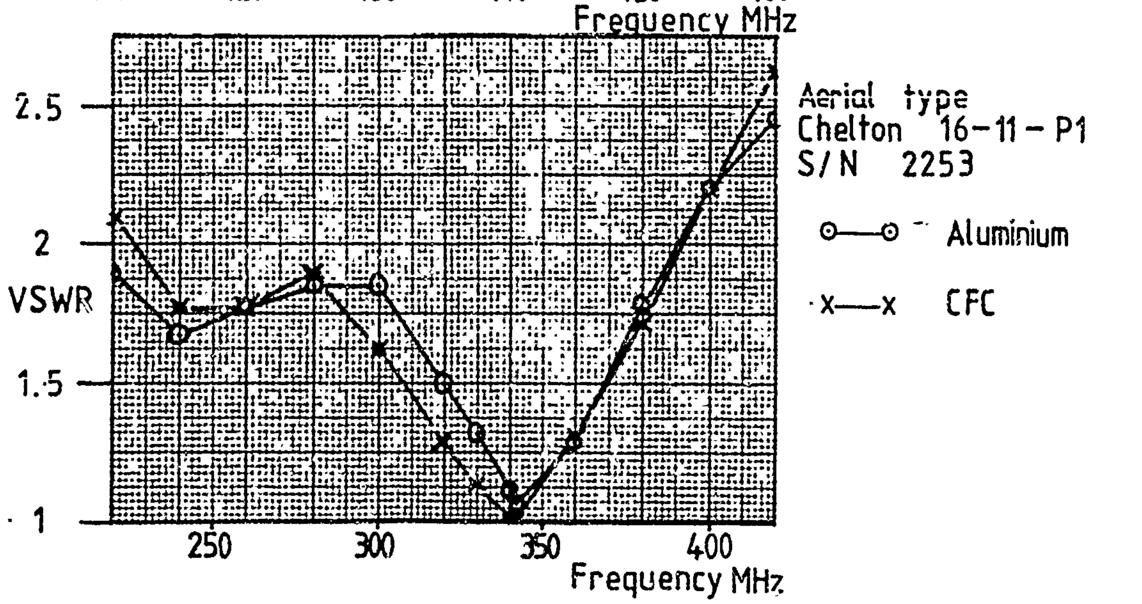


Figure 6 Comparison of VSWR for aerials mounted on CFC and aluminium cylinders

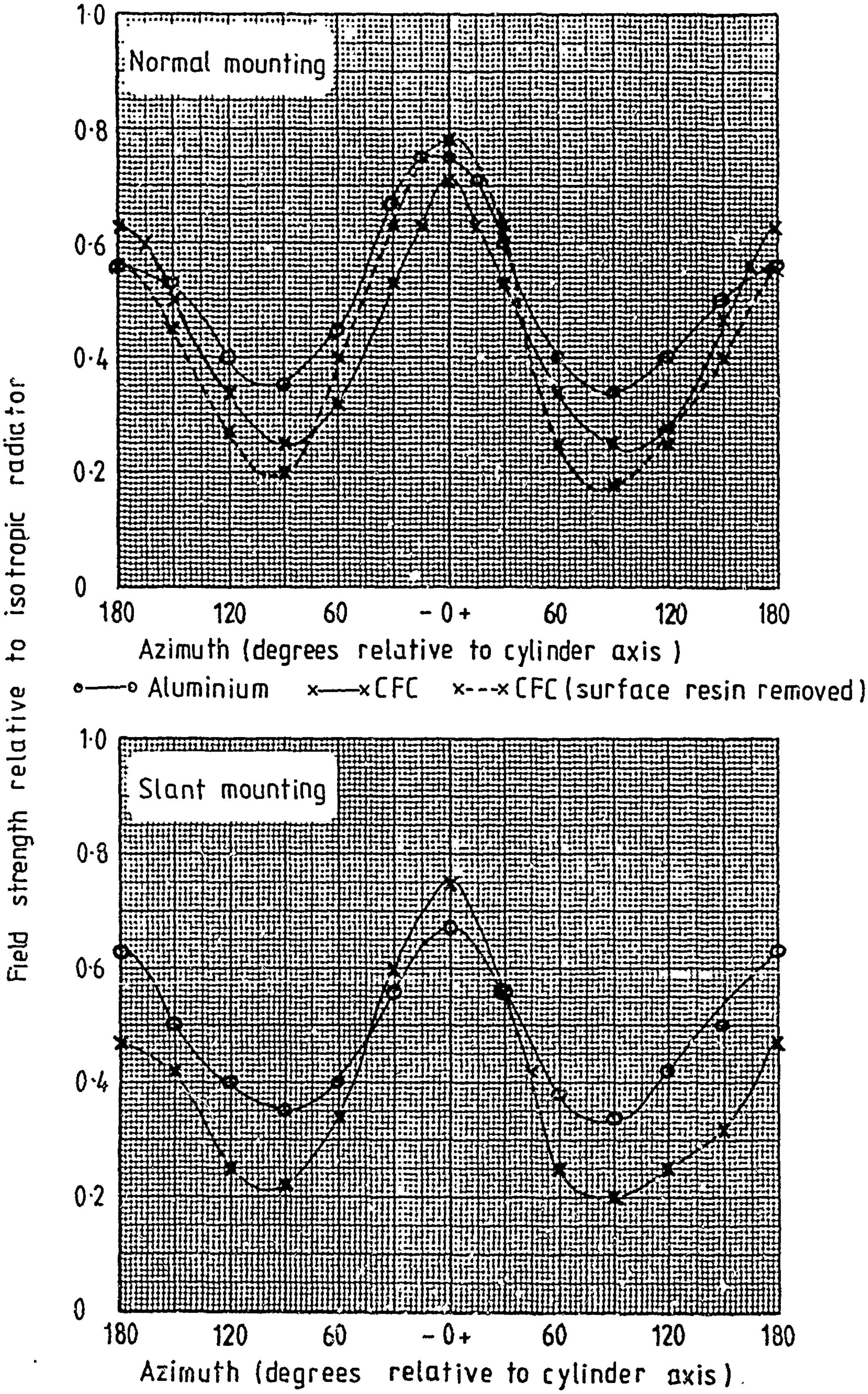


Figure 7 Radiation patterns for a Chelton 21-4B aerial radiating at 118 MHz and mounted on CFC and aluminium cylinders

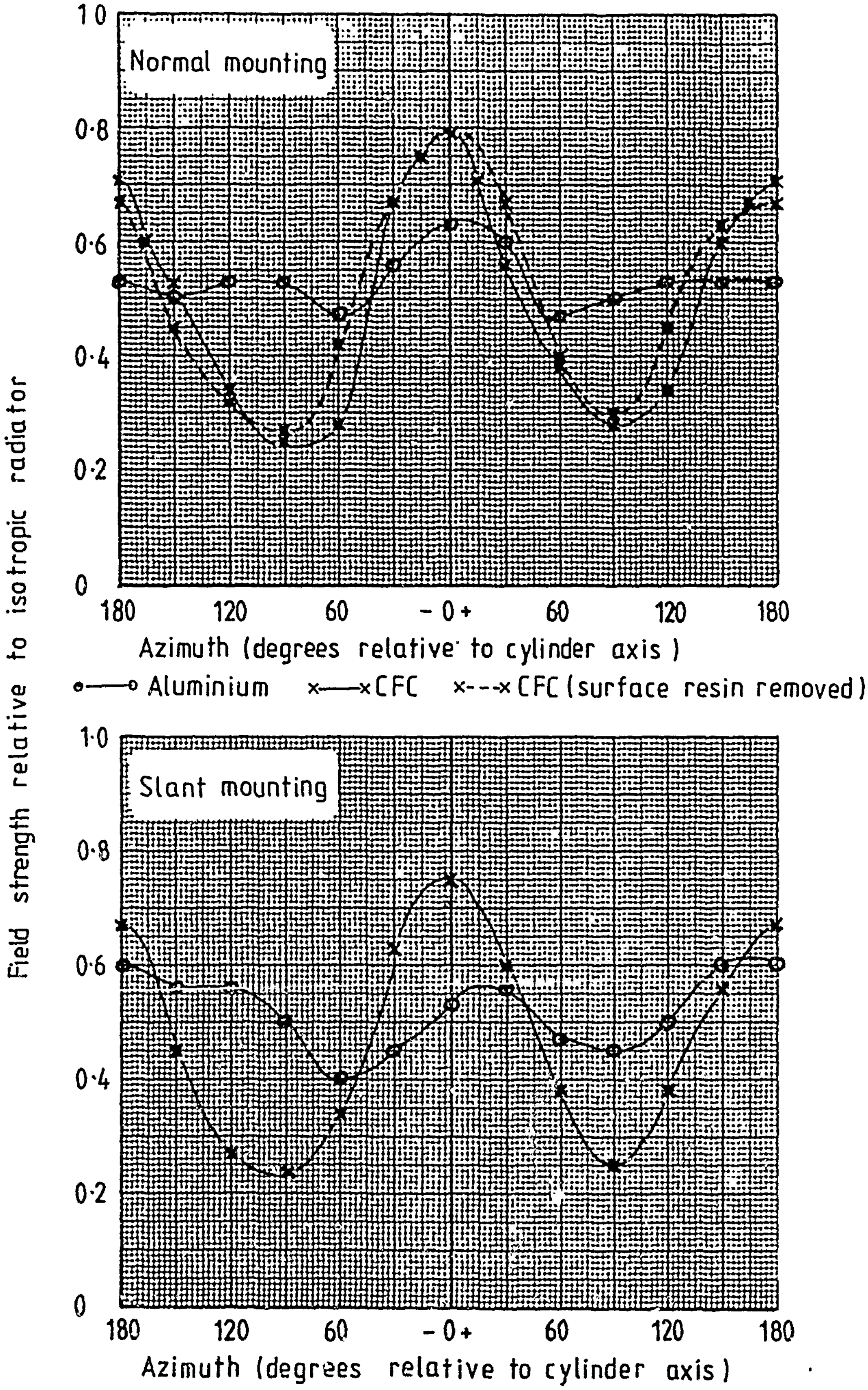


Figure 8 Radiation patterns for a Chelton 21-4B aerial radiating at 127 MHz and mounted on CFC and aluminium cylinders

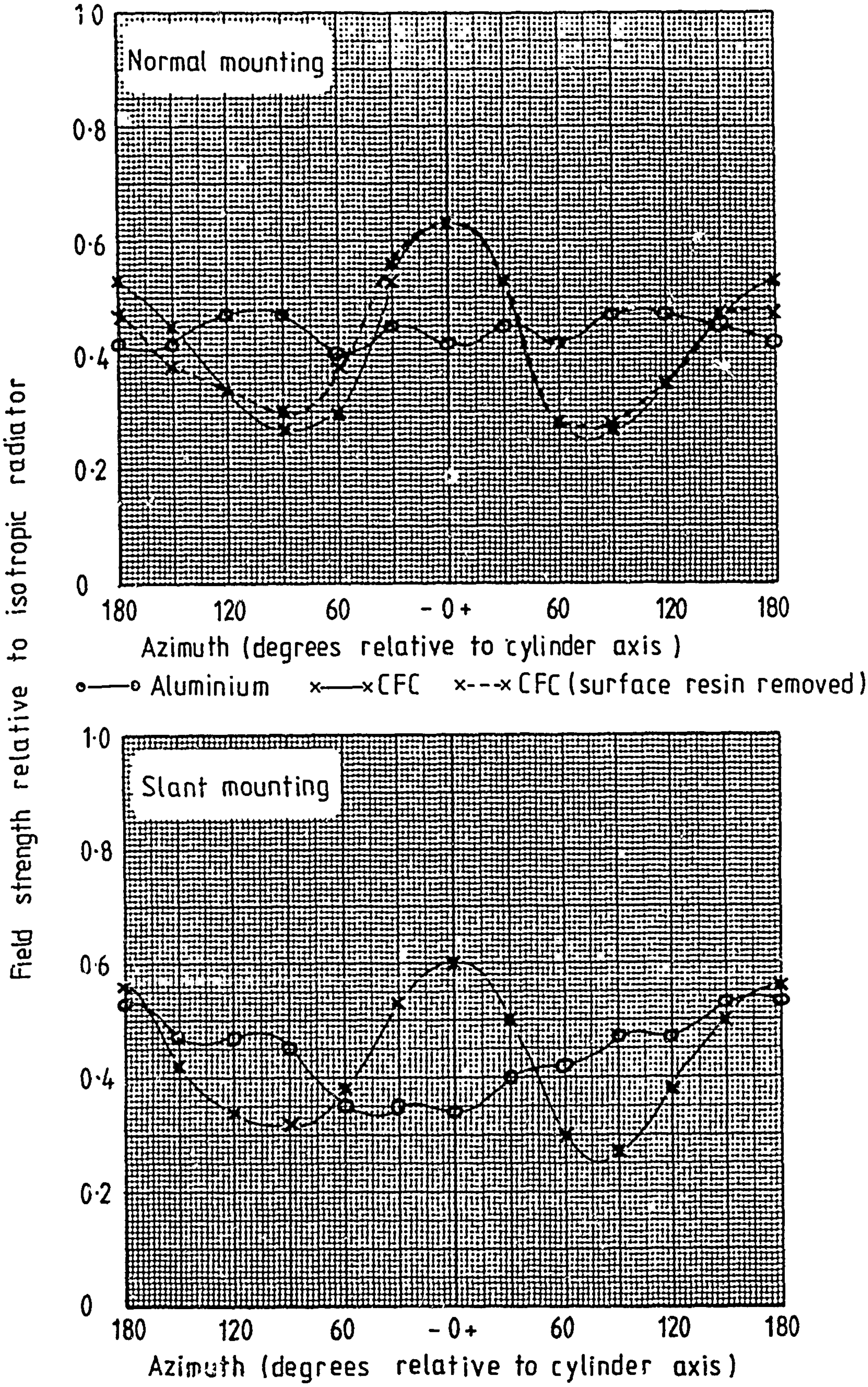


Figure 9 Radiation patterns for a Chelton 21-4B aerial radiating at 136 MHz and mounted on CFC and aluminium cylinders

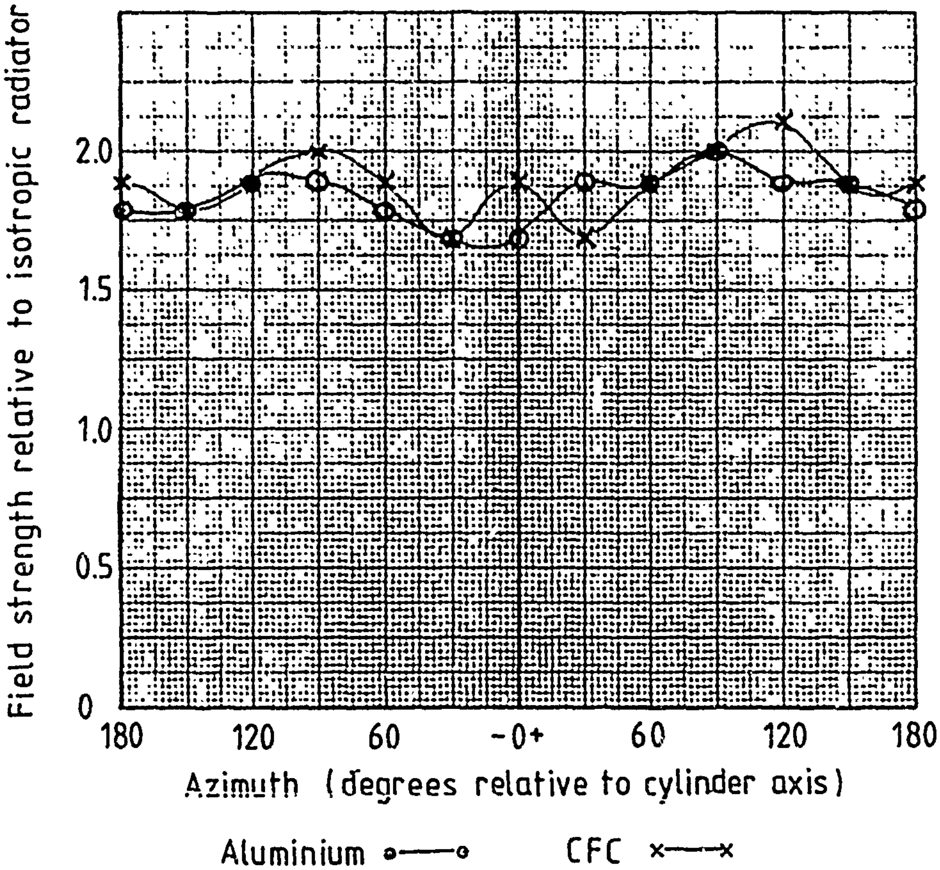


Figure 10 Radiation patterns for a Chelton 16-11-P1 aerial radiating at 300 MHz and mounted on CFC and aluminium cylinders

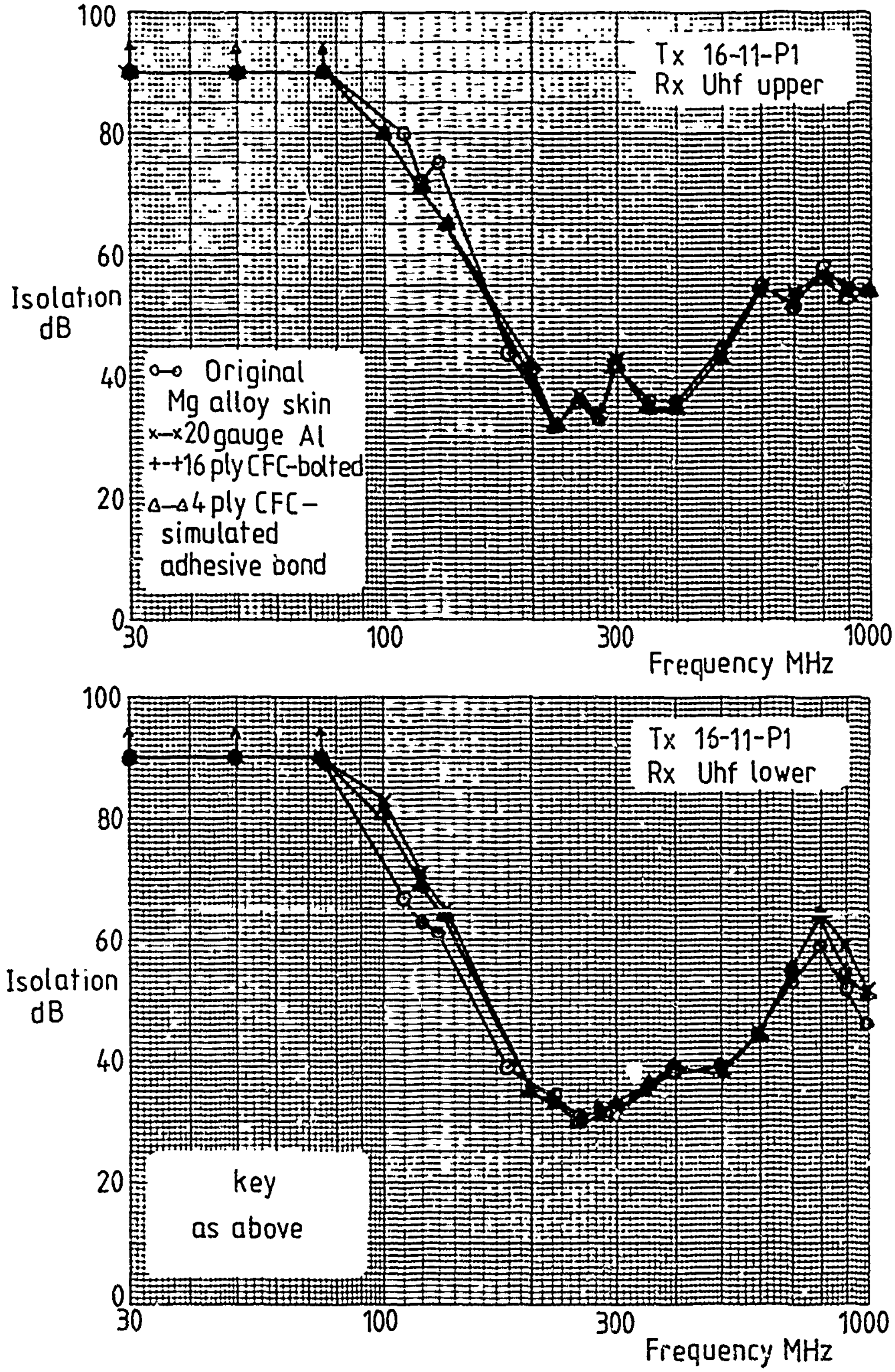
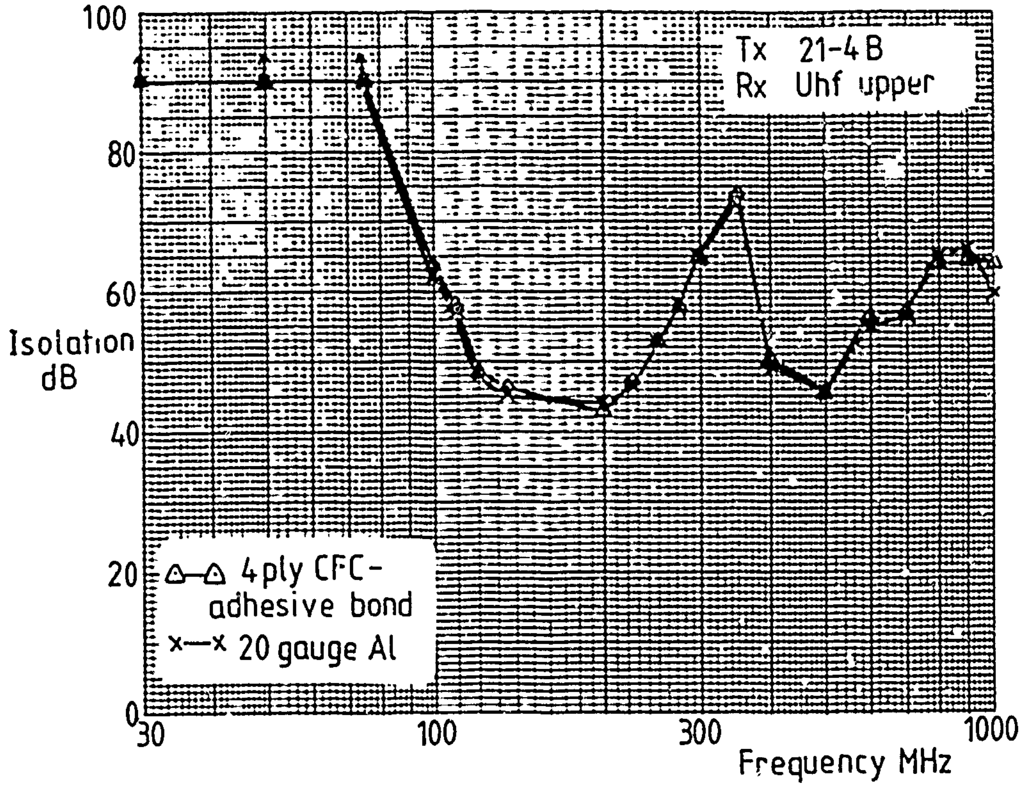


Figure 11 Aerial isolation for Chelton aerial type 16-11-P1 mounted on various test panels



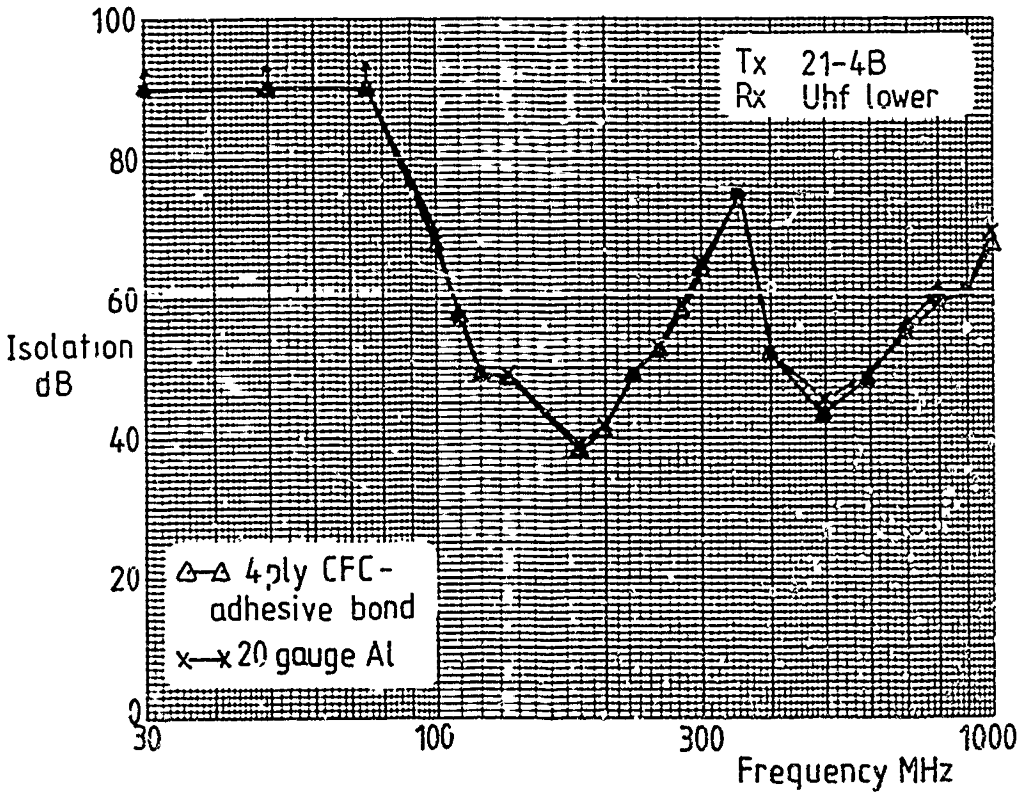


Figure 12 Aerial isolation for Chelton aerial type 21-4B mounted on various test panels

EMC IMPLICATIONS OF USING CFC MATERIALS IN AIRCRAFT MANUFACTURE

A McHale

SUMMARY

Results of the ERA investigations into the rf properties of CFC are summarised and problem areas highlighted. The implications of these results on the EMC of CFC aircraft are discussed and broad recommendations given.

CONTENTS

1 INTRODUCTION

The essential electrical difference between CFC and conventional metals used in airframes is its resistivity at d.c. and rf. At d.c. the resistivity of a wide range of CFC samples has been measured and the results, in Chapter 2, show values of 20 - 150 $\mu\Omega$.m (excluding unidirectional samples which gave values of upto 1100 $\mu\Omega$.m). This compares with 0.052 $\mu\Omega$.m for a typical aluminium alloy used in aircraft construction, a ratio of about 1000 for typical CFC samples. In addition, the resistance/frequency characteristic is of the same general form as that for homogeneous material, in that it appears to exhibit a skin effect, although some of the variations have yet to be fully explained. A considerable amount of experimental data has been accumulated. This data has been included, in full, in chapter 2 to facilitate future investigation by those who would further address this subject.

Although the influence of resistivity on the specification, design, construction and operation of aircraft with CFC in their structures has not yet been examined, the results of this investigation do indicate that major problem areas will arise because of the characteristics of the material at hf and below. At vhf and uhf the results suggest that electromagnetic problems associated with CFC will be less severe than at hf.

2 ELECTROMAGNETIC PROBLEM AREAS ASSOCIATED WITH CFC MATERIALS

Before this investigation commenced several areas were postulated as being potential problem areas. Those covered in this work include :

a) Aerial installation at vhf and above
b) Screening at vhf and above
c) Screening at hf and below
d) Bonding and jointing

The significance of each of these is described in the remainder of this section.

2.1 Aerial installation at vhf and above

This is unlikely to be a major problem. Tests using a typical uhf aerial mounted in turn on a CFC and an aluminium cylinder yielded very similar radiation pattern and VSWR results. Similar tests using a typical vhf monopole showed the radiation pattern to be less uniform and the VSWR to be greater (although still within the manufacturer's specification) when mounted on the CFC cylinder. These differences in the vhf results may in part be due to differences in the dimensions of these cylindrical ground planes. No problem is therefore envisaged in aerial installation at vhf and above although at vhf there may be minor degradation in performance if standard aerials are mounted on CFC.

2.2 Screening at vhf and above

The screening properties of a CFC or part CFC structure at vhf and above are unlikely to be significantly worse than those of an equivalent metal structure. Screening at these frequencies is largely determined by the presence of apertures (such as doors, windows or inspection panels) and the electrical quality of the joints between panel sections. Electric screening results for the Wessex, Chapter 7, show little difference between metal and CFC panels at vhf and uhf. The screening of the original tail cone was, however, no better than 30 dB over much of these frequency ranges ; this being due to apertures and the method of jointing between panel sections that was used in the construction of the helicopter. Tests using the copper enclosure, however, showed greater screening values for CFC panels than were measured using the Wessex tail cone. Screening in excess of 50 dB, over the range 30-1000 MHz, was common and, when electrical contact was made to the carbon fibres at the panel edges, frequently exceeded 90 dB. The question of bonding and jointing is dealt with below but as far as the screening at vhf and above is concerned once precautions are taken to achieve electrical contact at joints, sufficient for magnetic screening at hf, then screening at vhf and above should be no worse than for an all metal structure.. Even in a metal aircraft, however, it is not wise to place reliance on the screening afforded by the fuselage for the protection of sensitive electrical and electronic systems because of impedance discontinuties.

2.3 Screening at hf and below

The impedance of CFC material, at hf and below, is much greater than for aluminium alloys and, as a consequence it offers much less screening to magnetic fields. This factor is particularly important in the electromagnetic compatibility of aircraft systems as on-board hf installations in conventional metal aircraft presently cause considerable problems and it is likely that there will be even more penetration of hf energy through CFC skins. Results for the Wessex helicopter, Chapter 7, indicate that penetration of rf from an hf installation through 16 ply panels is up to 3 times greater, and through 4 ply CFC panels (such as may be used for fuselage skins) up to 10 times greater than through an aluminium test panel. The screening measurements on cylindrical structures, Chapter 8, indicate similar results. In this case, penetration through 16 ply CFC and through the aluminium is similar at 30 MHz. Below this frequency however the greater penetration is through the CFC cylinder, below 8 MHz being more than 10 times greater than through the aluminium cylinder.

2.4 Bonding and jointing

During the investigation it became particularly apparent that the screening performance was affected by the quality of electrical contact between the carbon fibres at panel edges and adjacent panels or the supporting structure. Resin systems presently used in CFC materials are non-conducting and hence to make electrical contact to the carbon fibres the panel must either be drilled, milled or the surface abraded to expose the fibres. In the laboratory, surface abrasion followed by electroless copper plating techniques provided excellent electrical contact to the fibres. This method is however not practicable for aircraft manufacture.

Screening results have been obtained for CFC panels mounted or jointed using bolting, riveting and adhesive bonding techniques. Drilled panels were fastened at pitch centre diameters of between 28 and 60 mm for countersunk bolts and 25 mm for rivets. Generally these methods of fastening caused little reduction in screening; however when adhesive bonding techniques were used the resulting joint was 'open circuit' and

the screening greatly reduced. Results of penetration of magnetic field at hf for adhesively bonded panels installed on the Wessex showed the penetration to be largely independent of the panel thickness and to be 30 times greater than through the aluminium test panel. Tests on the CFC cylinder with one joint insulated to simulate an adhesive bond indicate a penetration 100 times greater than for the aluminium cylinder.

3 IMPLICATIONS FOR EMC IN AIRCRAFT

Results in this report have indicated that electromagnetic screening, aerial installation and operation at vhf and above are unlikely to cause greater problems on CFC or part CFC aircraft than are currently experienced on all-metal aircraft.

This statement is based on the inherent characteristics of the materials examined. Significant imperfections, such as resonant slots will cause EMC problems throughout the frequency range if bonding methods are inadequate.

At hf and below, however, there are likely to be major electromagnetic compatibility problems on CFC aircraft. The two main factors involved are those discussed in sections 2.3 and 2.4, namely the high impedance of CFC at hf and the difficulty of ensuring sufficient electrical contact at the joints. For the joints to have a minimal effect on the screening the impedance across the joints needs to be much lower than the impedance across the CFC panels.

The screening in the hf band for CFC panels with poorly conducting or insulated joints has been found to be little more than 20 dB. At this level of screening the penetration, through the fuselage skin, of rf energy from on-board hf transmissions and from external sources (including EMP and lightning) is expected to be much greater than for conventional metal aircraft. It is known that the operation of transmitters in the hf band may produce fields of some hundreds of volts per metre immediately outside an aircraft and so equipment within the aircraft could encounter field of some tens of volts per metre. Accordingly it is likely that electromagnetic interference susceptibility specifications for avionic

systems will need to be more severe in the hf band. Also care will need to be taken in the siting of avionic systems in order to minimise coupling of rf energy to these systems.

Compatibility problems will be partially alleviated if care is taken to ensure effective electrical continuity at joints in the CFC fuselage. To this end, the use of adhesive bonding without alternative means of maintaining electrical continuity is to be avoided.

An additional problem area, although not directly a subject of this investigation, concerns the operation of hf transmitters on CFC aircraft. In general present hf systems use either wire or notch aerials. Wire aerials operate counterpoised against the fuselage skin whereas in the case of notch aerials the whole aircraft structure acts as the radiating element. For both types of aerial system the deficiencies of CFC material in the hf band, both in its high resistivity and the problem of achieving low values of joint impedance, are likely to reduce the system performance, both in terms of its efficiency and usable frequency range.

4 CONCLUDING REMARKS

The ERA investigation programme over the last four years has amassed much data on the rf properties of CFC materials. From this data two major problem areas have been identified, namely the high resistivity of the material and the difficulty of ensuring sufficient electrical continuity across joints (due to the insulating properties of the resin systems). Both these deficiencies result in lower screening, at hf and below, than is expected for metallic aircraft and accordingly the penetration of rf energy into the aircraft from both on-board hf transmitters and from external sources, including EMP and lightning, will be greater. These deficiencies are not such as to inhibit the use of CFC in aircraft. There must, however, be close liaison between materials, structures, electrical and EMC specialists to ensure optimum overall design, particularly with regard to bonds and joints. Avionic syst.ms for inclusion in CFC aircraft will also need to be subject to more severe EMC susceptibility requirements, particularly in the hf band and more importance than perhaps has been the case for metal aircraft will need to be placed on EMC design, including positioning, screening and bonding of system installations.

CHAPTER 11

STUDY AND SURVEY OF PUBLISHED WORK ON THE ELECTRICAL AND RF PROPERTIES OF CARBON FIBRE COMPOSITE MATERIALS INCLUDING WORK ON ELECTROMAGNETIC SCREENING

B W Smithers

1 INTRODUCTION TO LITERATURE SURVEY

This survey was aimed at providing details of work on these electrical and rf properties published in the period 1966 to mid-1981. Some measurement techniques developed prior to this period have also been included in the survey.

Sources such as Science Abstracts, D of I Index to US NTIS microfiche and IEEE Symposium Records have been examined. Much of the literature has been obtained, and, where possible, a brief note is given on the content of each work. Where measurement techniques are described, it should be borne in mind that some may be inapplicable, or of limited application in the area of CFC materials.

It should be noted that, as the survey is directed solely towards electrical and rf properties, many well-known and significant publications relating to CFC materials have not been included as they did not contain information directly relevant to this study.

2 LITERATURE SURVEY

1 Allen, J; Gajda, W; Griffin, D; Harrington, R; Heintz, R; Joy, E; Lyon, J and Walker, W: 'A technology plan for electromagnetic characteristics of advanced composites', Rome Air Development Centre, Phase Report, RADC-TR-76-206, July 1976.

This report is a comprehensive survey of the influence of composite materials on aircraft design and other aspects such as:

Fabrication, physical characteristics, hazards, fundamental parameters, measurement techniques, modelling techniques, shielding, aerial performance and computer-aided electromagnetic field analysis.

2 Skouby, C D: 'Electromagnetic effects of advanced composites', McDonnell Aircraft Company Report MDC A3441, April 1975. 'Electromagnetic effects of advanced composites', Final Report for Office of Naval Research, Dept. of the Navy, NTIS Ref.AD010882.

Measurements of shielding effectiveness, generally 40 kHz-10 GHz (coaxial line or box measurement), for graphite and boron composites. AD010882 contains more results and details than MDC A3441.

3 Kim, D G; DuBro, G A and Beavin, R C: 'Measurement of advanced composite materials shielding effectiveness', Technical Report AFFDL-TR-74-30, June 1974 (Wright-Patterson AFB).

Measurements for boron and graphite composites over ranges 100 Hz to 1 MHz. Samples were tested with and without conductive overlays. A loop method was used to measure shielding of samples including aluminium. Negative attenuation effects were noted when using aluminium honeycomb material and are said to be due to focussing phenomena.

4 Strawe, D and Piszker, L: 'Interaction of advanced composites with electromagnetic pulse (EMP) environment', Boeing Aerospace Company, Document D180-18879-1, Technical Report AFML-TR-75-141, September 1975.

Shielding effectiveness measured by box method and some results are given for boron and hybrid graphite/glass composites over the range 0.1 to 100 MHz.

Composites and coating materials were fabricated into cylindrical specimens to obtain values for surface transfer impedance, etc. Joints were evaluated using a quadrax test arrangement. Some cylindrical specimens were also tested in an EMP simulator.

5 Strawe, D and Piszker, L: 'Electromagnetic shielding characteristics of advanced composites in the 10 kHz to 100 MHz frequency range', Final Report, Boeing to AFML 1975, under Contract F33615-74-C-5158.

This report was not available but the contract number is that applicable to the report described above and it is likely that this contains all the relevant information.

6 Hiebert, A L: 'Advanced composites, electromagnetic properties, vulnerabilities and protective measures', Report R-1979-AF, May 1977 (Rand Corporation).

Description of type of information that author believes necessary for the assessment of the electromagnetic properties and vulnerabilities and protective measures in the use of composite materials.

Composite structure, current and potential uses, energy sources and environments (e.g. lightning), shielding effectiveness are discussed. A suggested format for a measurement and analysis data base is given.

7 Allen, L; Walker, W F and Siarkiewicz, K R: 'An investigation of the electromagnetic properties of advanced composite materials', IEEE 18th EMC Symp. Record, July 1976, pp.174-177.

This paper reviews the current state of knowledge of the characteristics of advanced composite materials, and notes that lightning effects have been studied to a greater extent than other properties. Investigations of basic properties of these materials had not been undertaken, but experimental investigations of electromagnetic shielding have been made in specific geometries. Seams and apertures also require study. The rest of this paper suggests techniques for acquiring basic parameters of composite materials and shielding characteristics. References are given as sources of these techniques.

8 Blake, C L: 'Composites - their electrical and electromagnetic impact', IEEE 18th EMC Symp. Record, July 1976, pp.170-173.

This paper only points out areas of interest when composites replace metal. These are given as shielding effectiveness, electrical systems, static electricity, aerial performance and radar cross-section. Comments are made on each aspect, e.g. under shielding effectiveness, it is stated that reductions in airframe shields will force the shielding burden to the internal sub-systems.

9 Dow, M B: 'Trends in applications of advanced composites to commercial aircraft', p.169 (Abstract only).

Abstract states that the paper discusses NASA flight service programmes, where composites have been introduced into CH-54B helicopter tail cone and C-130 transport aircraft wing boxes. Experience with advanced composites on L-1011, B-737 and DC-10 commercial transports is also given. Future programmes are also presented.

10 Strawe, D: 'Shielding characteristics of advanced composites', IEEE 18th EMC Symp. Record, July 1976, pp.180-185.

Discussion of shielding, aperture effects and transfer impedance measurements based on work described in Ref. 4 above.

11 Skouby, C D: 'Effects of advanced composites on shielding and aerial performance', IEEE 18th EMC Symp. Record, July 1976, pp.192-197.

This paper based on work described in Ref. 2 above.

12 Kung, J T and Amason, M P: 'Lightning protection design concepts for advanced composite structures', IEEE 18th EMC Symp. Record, July 1976, pp.186-191.

This paper describes two design concepts:

(a) the isolation concept where graphite/boron composite skins are covered with high dielectric strength material and;

(b) the conductive concept where graphite composite structures may safely conduct lightning currents. The application of metal strip protection is discussed.

13 Zboril, F R: 'Aircraft antennas on new non-metallic materials', Fifth European Microwave Conference, Hamburg, 1-4 September 1975, pp.658-662.

Lightning protection, non-conductive or conductive is discussed. Reflection characteristics, panel transmissibility and waveguide measurements of permittivity are also stated to have been made. Radiation pattern of a monopole at centre of square ground plane is stated to be identical to that found with aluminium ground plane. Reflection properties differed by as little as 1% when compared with aluminium alloy. Power handling of kW transmitter outputs found to be comparable to aluminium skins.

14 Cook, J: 'Dielectric and conductivity properties of imperfectly aligned fibrous materials', ERDE Report TR142.

This work relates to partially oriented mats of asbestos or silicon carbide whiskers. The capacitance of a pair of interdigital circuit boards is measured with the test sample sandwiched between them. The high permittivities observed for these materials is explained by the presence of high conductivity fibres not in contact with each other. The measurement is proposed as a method of assessing the degree of alignment of fibres and is inapplicable for high conductivity materials such as carbon-fibre.

15 Schulz, R B: 'RF shielding and electrical properties of boron and carbon-fibre reinforced composites', IEEE 14th EMC Symp. Record, July 1972, pp.180-184.

Samples of carbon or boron composite material ranging from 230 x 160 x 2.64 mm to 380 x 270 x 0.953 mm were used to separate small source and receiver coils placed at the centre of the sheets. Control sheets of aluminium were also used. Shielding effectiveness from 10 MHz to 500 MHz was measured. The main conclusions relating to CFC materials were:

(1) Crossed carbon-fibres have significant shielding properties at higher frequencies. Effect can only occur because fibre to fibre connections occur at intersections.

(2) Electrical conductivity of crossed carbon-fibre composite is about four orders of magnitude worse than aluminium.

16 Bakker, W F: 'The effect of lack of symmetry in honeycomb shielding panels', 12th Symp. Record, July 1970, pp.113-119.

This paper notes that many honeycomb panels are electrically non-symmetrical where cross-wise resistance can greatly exceed length-wise resistance. The effect of this lack of symmetry on shielding effectiveness is calculated, though such calculations are questionable. Tests on samples of honeycomb material from several manufacturers indicated the wide variations obtainable. Various procedures for metallic bridging of the epoxy bond give improvement but most have not been employed commercially. A panel constructed of two honeycomb panels mounted with their foil directions at right angles gives uniform shielding against all orientations of electromagnetic fields.

17 Pownall, P: 'Preliminary tests on the screening performance of carbon-fibre panels', CLSU Memo No.51, Engineering Design Division, Culham Laboratory, May 1977.

CFC panels, 292 mm square x 0.62 mm were clamped over a hole in an aircraft fuselage with overlapping edges insulated from the airframe. The latter was connected as the inner conductor of a coaxial system and excited by a high current generator at a frequency of 270 kHz. Voltages induced on wiring within the airframe were measured and compared with those obtained using an aluminium panel. Little screening effect was obtained from the carbon-fibre composite panel.

18 Burrows, B J C; Pownall, P and Luther, C A: 'Hunter induced voltage programme, (1) preliminary measurements', CLSU Memo No.48, Engineering Design Division, Culham Laboratory, November 1976.

This report describes the test arrangement referred to in Ref 17 above D.C. resistance measurements were made across various parts of the assembly and a.c. tests established peak currents, inductance and dI/dt. Current distribution in the airframe was measured with search coils and results compared with predicted values.

19 Burrows, B J C; Luther, C A and Pownall, P: 'Further tests on screening due to CFRP aperture covers', CLSU Memo No.59, Culham Laboratory, November 1977.

The screening effectiveness of CFC panels of various thicknesses are compared in the arrangement described in Refs 17 and 18 above. Well bonded panels have a significant screening effect which are strongly dependent on thickness. Insulated panels give negligible attenuation. Estimations of induced voltages on wiring behind CFC panels are feasible.

20 Burrows, B J C; Luther, L A and Pownall, P: 'Resistance measurements on bulk CFRP and on metal/CFRP joints', CLSU Memo No.56, Engineering Design Division, Culham Laboratory, October 1977.

Current from a high current capacitor source was made to flow in a rectangular coaxial system incorporating CFC sheets. Diagnostic wires monitored potential differences in the sheets. Action integrals, transferred charge, calculated bulk temperature rise and other parameters were obtained. Resistance of panels and panel to indium lapped joints were also measured.

Panel conductivity in the bulk fibre, well removed from joints was very linear. At joints non-linearity was observed. Ageing effects during a series of high current pulses were noted.

21 Bagley, G: 'Notes on rf properties of carbon-fibre reinforced plastics', RAE, October 1977.

This paper notes the electrical and rf functions of an airframe and problems brought about by the inclusion of such high resistivity materials. Some measurements with a monopole aerial or a CFC groundplane at uhf indicated no significant difference in performance when compared with such an aerial mounted on an aluminium alloy sheet. Resistance measurements made up to frequencies of 900 MHz indicated no measurable skin effect in a CFRP sample. Some desirable features of further work are listed together with unknown properties involved with aircraft assembly methods.

22 Burrows, B J C: 'Lightning hazards to aircraft aerial systems. Susceptibility and high current test techniques', Report CLM/RR/M5/3, CLSU, Culham Laboratory, May 1977.

The natural lightning environment is described together with the accepted test waveforms for laboratory simulation tests on aircraft components including aerials. The risk of damage to aircraft equipment and installations is considered. A new method of classification for equipment damage is given. Methods for the calculation of minimum safe cross-sectional area for conductors and the magnitude of injected and induced voltages caused by strikes to aerials are also to be found. High current test techniques are described together with techniques for simulating the effects on aerials of induced voltage due to current along the airframe.

Data on aerial strikes on military and civil aircraft are included and conclusions regarding susceptibility of various items are drawn. Design recommendations to minimise the risk of damage are given.

23 Fothergill and Harvey Limited: 'CARBOFORM', preimpregnated high modulus carbon-fibre, catalogue, 1970.

General information on properties and uses including types of resin. Dielectric constant at 1 MHz for unidirectional Type 1 (high modulus) reinforced epoxy Novolac is given as 50-70. Type 2 fibre is known as high strength and Type A has lower mechanical properties than Types 1 or 2 but is appreciably cheaper.

24 Rogers, K F and Kingston-Lee, D M: 'The preparation of composite heating panels', RAE Technical Memo MAT 158.

Various types of panel incorporating carbon-fibre are described and it is shown that metal strips can be bonded into the composite material at the edges and make satisfactory connection.

25 Miedzinski, J: 'Electromagnetic screening - theory and practice', ERA Technical Report M/T135, 1959.

This is a comprehensive treatment including theory of screening, properties of screening materials, properties of practical screened enclosures and a review and discussion of literature.

26 Miedzinski, J: 'Testing of screened enclosures', ERA Technical Report M/T132, 1958.

Insertion loss of an enclosure is defined followed by sections on principle of testing, fundamental investigation of insertion loss, simplified measurement of insertion loss, detection of leaks, testing of enclosures having dimensions comparable with wavelength, dependence of test results on experimental layout, production testing and conclusions and references.

27 Whitehouse, A C D: 'Screening : new wave impedance for the transmission line analogy', Proc. IEE, Vol.116, No.7, July 1969, pp.1159-1164.

Using the modifications to wave-impedances associated with magnetic dipole and current-loop sources described in this paper, the author shows

that agreement between theory and measurement published by other workers, is improved. The treatment described in Ref.25 already contains these correct wave-impedance factors.

28 Moser, J R: 'Low-frequency shielding of a circular loop electromagnetic field source', IEEE Trans. on EMC, Vol.EMC-9, No.1, March 1967, pp.6-18.

Of general applicability in the calculation of shielding effectiveness of sheet material. This is a paper where agreement between theory and experiment may be improved by adopting the correct wave-impedance referred to in Ref.27 and also to be found in Ref.25.

29 O'Young, S L; Goldman, R and Jargensen, L: 'Survey of techniques for measuring rf shielding enclosures', IEEE Trans. on EMC, Vol.EMC-10, March 1968, pp.7?-81.

Methods of testing shielding enclosures from 3 kHz to 20 GHz are discussed and tabulated, and a weighting system is given, attached to factors such as measurement accuracy, frequency range, complexity of test set-up, etc. A useful list of references is included.

30 Ryan, C M: 'A computer expression for predicting shielding effectiveness for the low-frequency plane shield case', IEE Trans. on EMC, Vol.EMC-9, No.2, September 1967, pp.83-94.

This is a computer programme for a infinite plane shield developed for frequencies below 50 kHz. Excellent agreement is claimed for values obtained experimentally for aluminium, copper and steel.

31 Bondarenko, N L; Shkarlet, Yu M and Chub, A F: 'Reflection and screening of the non-stationary field of a turn by a conducting medium', Sov J Nondestruct. Testing (USA), July-August 1973, pp.482-487.

Accurate solutions are given describing the reflective and screening properties of a multilayer conductive medium probed by a loop aerial excited by a current step. Approximate formulas for engineering calculations have also been derived.

32 Robinson, W A and Madle, P J: 'Surface impedance tester', US Patent No.3995213, 30 November 1976.

Designed for the measurement of the resistivity and permeability of metal sheets. A pulse of current is injected by the outer probes of a linear four-probe system. The parameters of interest are evaluated from the time dependence of the decay of voltage measured by the two inner voltage probes. Its application to composite materials is doubtful.

33 Neighbor, J E: 'Eddy-current method for measuring anisotropic resistivity', J Appl. Phys, Vol.40, No.8, July 1969, pp.3078-3080.

The eddy-current method for measuring resistivity is extended to situations in which the resistivity is anisotropic. The author suggests that in most cases of interest, the full resistivity tensor can be obtained from eddy-current measurements.

34 Bean, C P; DeBlois, R W and Nesbitt, L B: 'Eddy current method for measuring the resistivity of metals', J Appl. Phys, Vol.30, 1959, pp.1976-1980.

This paper is referred to by author of Ref.33. Measurement made by noting rate of decay of flux from a bar situated in an external magnetic field that has been rapidly reduced to zero. Measurements possible from 10^{-13} to 10^{-5} Ωm.

35 LePage, J; Bernalte, A and Lindholm, D A: 'Analysis of resistivity measurements by the eddy-current decay method', Rev. Sci, Inst, Vol.39, 1968, pp.1019-1026.

As Ref.32, but measurements limited to range 10^{-13} to 10^{-7} Ωm.

36 Hale, D K: 'The physical properties of composite materials', J Mater SCI, Vol.11, No.11, November 1976, pp.2105-2141.

This is a paper of wide scope and includes a discussion of the relationships for permittivity and electrical conductivity in axial and transverse directions for a composite containing rods or fibres of uniform cross-section aligned in one direction.

37 Price, W L V: 'Extension of van der Pauw's theorem for measuring specific resistivity in discs of arbitrary shape to anisotropic media', J Phys. D, Vol.5, 1972.

The method of measuring resistivity described by van der Pauw in 1958 and valid for isotropic materials is shown to be applicable to samples of anisotropic materials, where it measures the geometric mean of the principal components of the resistivity tensor in the plane of the sample.

The author states that an isotropic body may be regarded as the special case of an anisotropic one, in which the principal components of the resistivity tensor are all equal. It follows, therefore, that van der Pauw's method may be applied to any material, and that it always measures $(\rho_1/\rho_2)^{\frac{1}{2}}$, where ρ_1 and ρ_2 are the principal components of the resistivity tensor in the plane of the sample.

38 Miller, G L; Robinson, D A H and Wiley, J D: 'Contactless measurement of semiconductor conductivity by radio-frequency free carrier power absorption', Rev. SCI. Instrum, Vol.47, No.7, July 1976, pp.799-805.

Power absorption in a thin semiconductor slice in an oscillating magnetic field is shown to be proportional to material conductivity. A limiting sensitivity of about 10^{-5} ohm per square is claimed and is suitable for essentially any conducting material from semiconductors to metals.

39 Crowley, J D and Rabson, T A: 'Contactless method of measuring resistivity', Rev. SCI Instrum, Vol.47, No.6, June 1976, pp.712-715.

The configuration adopted in the measurement described in this paper is claimed to perform absolute measurements of resistivity over a wide range of values for relatively small samples.

40 Holzschuh, T C and Gajda, W J, Jr: 'D.C. electrical behaviour of graphite fibres', IEEE 19th EMC Symp. Record, August 1977, pp.394-395.

It is noted that fibres produced by different companies had significantly different conductivities. Fibres from one source were examined individually by coating the ends of fibres with conducting paint to provide ohmic contacts. The fibres measured had an average d.c. conductivity of 2.06×10^4 Sm^{-1} with a range of 1.39 to 3.03×10^4 Sm^{-1}. Responses were linear with maximum fields of 4000 V m^{-1} applied.

41 Scruggs, L A and Gajda, W R, Jr: 'Low frequency conductivity of unidirectional graphite/epoxy composite samples', IEEE 19th EMC Symp. Record, August 1977, pp.396-402.

Measurements were made of current-voltage characteristics of unidirectional composites over the range d.c. to 1 MHz. Conductivities of 2×10^3 Sm^{-1} were obtained for currents parallel to the fibres and two orders of magnitude less for currents perpendicular to the fibres. Ohmic electrical contact to the fibres of the samples was made by vacuum evaporation of aluminium. Non-linearity occurs above 250 V m^{-1} for longitudinal currents and above 4000 V m^{-1} for transverse currents. Permeability approaches that of free space and laboratory measurements indicate that graphite epoxy is weakly diamagnetic with a susceptibility about 10^{-7} emu/gmOe.

Photographs of polished faces of unidirectional samples show that a high degree of fibre-to-fibre contact is present thus explaining the high level of transverse conductivity.

Capacitance experiments were undertaken, but are not described in this paper. It is noted, however, that experiments involving insulator-graphite-epoxy-insulator structures provide information concerning the electrical properties of the insulators only. Experiments free of error would allow the determination of resistance and capacitance of the graphite/epoxy alone. Since this is not possible, it is concluded that the permittivity of graphite/epoxy is indeterminate and attempts to measure permittivity of these materials over the frequencies of interest will yield meaningless results in view of the relatively large conductivities of the samples.

42 Kung, J T and Amason, M P: 'Electrical conductive characteristics of graphite composite structures', IEEE 19th EMC Symp. Record, August 1977, pp.403-408.

Lightning tests on composite panels and joints are described where a Thermovision mapping technique was used to record the temperature gradient on the sample surface. The structures tested were regarded as sufficiently conductive for the transfer of lightning currents. For receiving aerial applications, tests conducted at frequencies above 100 MHz, indicated that a graphite composite skin panel ground plane behaves similarly to the conventional metal ground plane.

43 Walker, W F and Heintz, R E: 'Conductivity measurements of graphite/epoxy composite laminates at uhf frequencies', IEEE 19th EMC Symp. Record, August 1977, pp.410-413.

Techniques for conductivity measurements above 100 MHz may be summarised as follows:

(1) Sample as partition in coaxial transmission line. Edge contact problems. E-field is radial and inter-relationship of the exciting field with the normal linear parallel fibre orientation in the composite sample may defy analysis.

(2) Unidirectional sample mounted between the two conductors of a strip line with fibres running vertically between the two conductors. Some suspicion of results, especially above 1 GHz. Contact resistance effects are ignored.

A more direct method was evolved where a unidirectional sample was incorporated as one of the 'strips', with fibres parallel to or perpendicular to the direction of primary propagation. Results at 1 GHz and 2 GHz are claimed to be encouraging and it may be possible to adapt the system to work down to at least 100 MHz.

44 Burrows, B J C; Luther, C and Pownall, P: 'Induced voltages in full size aircraft at 10^{11} A/sec', IEEE 19th EMC Symp. Record, 1977, pp.207-214.

This paper is based on Ref.18 above.

45 Brush, D R; Schulz, R B and Jorgensen, L: 'Low-frequency characteristics of rf shielding materials', IEEE Trans. on EMC, Vol.EMC-10, March 1968, pp.67-72.

Initial magnetic permeability and electrical conductivity for material in the form of a flat sheet, a box or any other configuration containing at least a six inch square flat surface are shown to be obtainable by a simple technique. The technique appears to be valid for isotropic materials only.

46 Owston, C N: 'Eddy current methods for the examination of carbon-fibre reinforced epoxy resins', Mater. Eval. (USA), Vol.34, Part 11, 1976, pp.237-244 and 250.

The author describes how fibres fully wetted by a resin matrix and remaining so during all stages of processing in a unidirectional composite would give a material which would not have significant conductivity in a direction perpendicular to the fibres. Complete wetting cannot be ensured, however, and pressure applied during moulding guarantees that fibre-to-fibre contact takes place at many points.

A transverse bulk resistivity 20 to 100 times the longitudinal resistivity is produced.

Eddy current testing for non-destructive examination of fibre volume fraction, fibre orientation and cracks is discussed.

47 Stern, R; Levy, M; Kagiwada, R and Rudnick, I: 'On the measurement of resistivity of metal bars by eddy current decay', Appl. Phys. Letters, Vol.2, Part 80, pp.80-81.

This paper describes a correction which may be applied to the method proposed in Ref.34, due to the finite time-constant of the primary coil. Methods are also described which reduce unwanted induced voltages.

48 Knibbs, R H and Morris, J B: 'The effects of fibre orientation on the physical properties of composites', COMPOSITES (GB), Vol.5, Part 5, 1974, pp.209-218.

Measurements of Young's modulus, resistivity and thermal expansion coefficient are described using either high modulus (Type I) or high strength (Type II) carbon-fibre with epoxy resins in a unidirectional structure.

Difficulty was experienced in making electrical contact over the whole sample section. After securing, the samples were ground and polished using diamond powder. Electrical contact was made by means of a mercury bath at each of the polished ends. Doubt remained concerning the adequacy of electrical contact and the accuracy of results is estimated to be ±7%.

Resistivity of the materials were obtained at angles from 0° to 90° of the longitudinal axis.

49 Beran, M J and Silnutzer, N R: 'Effective electrical, thermal and magnetic properties of fibre reinforced materials', J Compos. Mater. (USA), Vol.5, 1971, pp.246-249.

Bounds are derived for the effective conductivity (permittivity, permeability) of a fibre reinforced material in terms of volume fractions and a geometric factor describing the shape of the fibres.

50 Yanagida, H and Kawarada, H: 'Estimation of electrical conductivity of composite materials. (1) conductivity along grain boundary', Jap. J Appl, Phys. (Japan), Vol.13, Part 2, 1974, pp.244-248.

Concerned essentially with granular conducting or non-conducting inclusions in a matrix.

51 Natori, M; Kawarada, H and Yanagida, H: 'Estimations of electrical conductivity of composite materials. (II) numerical method for two-dimensional tetragonal texture', Jap. J Appl. Phys. (Japan), Vol.13, Part II, 1974, pp.1772-4.

Numerical methods are described for the computation of conductivity in a composite with granular inclusions.

52 Yamaki, J; Maeda, O and Katayama, Y: 'Electrical conductivity of conductive filler-polymer composites', Electr. Commun. Lab. Tech. J (Japan), Vol.26, Part 3, (In Japanese), 1977, pp.1159-1171.

Author's Abstract

Conductivity of composites containing conductive short fibres or particles was studied theoretically. The theory is based on probability of contact between the conductive fillers in the polymer. Effect of fibre length or particle size on conductivity was clarified from theoretical results in relation to the fibre contents. In the same way, conductivity dependence on composite compression was derived theoretically. These theoretical results coincided with the experimental results when the apparent contact resistivity between fillers was selected properly.

53 van der Pauw, L J: 'A method of measuring specific resistivity and Hall effect of discs of arbitrary shape', Philips Res. Rep., Vol.13, No.1, February 1958, pp.1-9.

A theorem is derived whereby the resistivity of a material in the form of a flat sample of arbitrary shape may be obtained by employing four point contacts on the periphery of the sample. (See also Ref.37).

54 Herring, T H: 'A design problem for the grounding session', IEEE EMC Symp. Record, 1972, pp.296-304.

The introduction to a session on grounding problems. This paper contains a brief reference to fibre structures.

55 Gajda, W R, Jr and Ajmera, P K: 'Sample standardisation in measuring the electrical properties of graphite/epoxy composites', submitted to the J of Composite Mater.

Not available for comment.

56 Gajda, W J, Jr: 'On the use of electrical dissipation factor to evaluate moulding quality in graphite/resin composites', submitted to Polymer Eng. and SCI.

Not available for comment.

57 Penton, A P et al: 'The effects of high intensity electrical currents on advanced composite materials', Naval Air Systems Command, Report U-4866, 1970.

Not available for comment.

58 Fisher, F A and Fassell, W M: 'Lightning effects relating to aircraft', Technical Report AFAL-TR-72-5, 1972.

Not available for comment.

59 Goodrum, G T: 'Lightning protection for advanced composite aircraft structures'. SAE Paper 700935, Lightning and Static Electricity Conference, December 1970, pp.223-231.

The structural advantages of composite materials are discussed. The influence of aluminium honeycomb cores, joint design and the protective effect of foil coating in relation to simulated lightning strikes are described.

60 'Protection of aircraft fuel systems against lightning', FAA Advisory Circular AC20-53, October 1967.

Not available for comment.

61 Amason, M P; Cassell, G J; Kung, J T; LaManna, J A and McCloud, W W: 'Aircraft lightning protection design considerations', Douglas Aircraft Company Tech. Paper 6043, Tech. Report AFAL-TR-72-325, Lightning and Static Electricity Conference, December 1972, pp.214-241.

Lightning protection design considerations for present and next generation aircraft are presented. A zone concept for lightning protection is described. General design considerations for aircraft constructed of boron and graphite epoxy composite and glass fibre reinforced plastic materials are presented.

62 Ketterer, J R: 'Composite development program - lightning effects on graphite/epoxy', McDonnell Aircraft Company, Report MDC A3715, Vol.III, February 1976.

Not available for comment.

63 Penton, A P and Perry, J L: 'Fundamental investigations of high intensity electric current flow processes and resultant damage in advanced composites', Philco-Ford Corporation, SAE Paper 700937, Lightning and Static Electricity Conference, December 1970, pp.253-295.

Tests with boron filament and CFC using Courtaulds HM-S tow or Hitco HMG-50 and Whittaker DEN 438/MNA resin are described. The limiting factor for CRC is said to be the resin matrix. Controlling factors are total electrical energy input and the fraction thereof dissipated in the form of heat.

64 'Advanced Composite Technology Fuselage Programme', AFML 71-41, Vol.VII, Convair Aerospace Division of General Dynamics, April 1974.

Not available for comment.

65 Thomas, R L: 'Effects of advanced composite structures upon antenna performance', Douglas Aircraft Company, Report MDC J7048, January 1976.

Not available for comment.

66 Zboril, F R: 'Communication and navigation antennas for airborne vehicles having non-metallic skin surfaces', Lockhead Report LR 26759, April 1975.

Not available for comment.

67 Sakovich, V N; Timofeeva, N I and Mordovin, O A: 'Chemical metallisation of graphite fibres', Fiz and Khim. Obrab, Mater. (USSR), No.2, (In Russian), March/April 1975, pp.112-115.

This paper gives a method for electroless plating of copper and nickel. The process for copper plating is essentially that given by Baskerville of Plessey Research (Caswell) Limited, although the present Russian paper omits to specify any salt of copper for the plating mixture.

Three electrolytes are proposed for nickel plating graphite. Electrolyte No.3 is simple in that it contains only two components, viz nickel sulphate and hydrazine sulphate, and coatings are produced free of phosphorus and sulphur.

68 Judd, N C W; Mathews, B J; Pritchard, G and Stokes, F C: 'The effects of aviation fluids on carbon/epoxy composite panels', Sampe Journal, Vol.13, Part 3, May/June 1977, pp.10-15.

Two epoxide resin systems preferred by the UK aircraft industry exposed to various fluids (hydraulic oils and lubricants, etc.), showed good resistance even at elevated temperatures. Void contents up to 5% did not seem to have a great effect either on inter-laminar shear strength or on resistance to the fluids.

69 Hudson, J L; Sneed, J W and Avery, L R: 'Technical Report AFML-TR-71-41, Advanced Composite Technology Fuselage Programme.

Not available for comment.

70 Hale, D K: 'The physical properties of composite materials', NPL Report IMS 27, January 1975.

Reference 36 appears to be based largely upon the contents of this report, the comments made regarding Ref.36 are applicable here.

71 'Carbon and graphite', Part 1, Fibres and fibre composites, Vol.2, NTIS/PS-77/0843, 1974 to July 1976.

Not available for comment.

72 'Carbon and graphite', Part 1, Fibres and fibre composites, Vol.3, NTIS/PS-77/0844, August 1976 to September 1977.

Not available for comment.

73 'Special Report: Aerospace Materials', Aviation Week and Space Technology, 26 January 1976, pp.42-45, 73-77, 95-96, 101 and 119-131.

This is a discussion of the applications of new and relatively new materials including carbon-fibre epoxy resin composites.

It is stated that processing characteristics of epoxy resins have been adopted as practical standards for measuring the processability of other potential matrix resins. Low temperature capability has restricted their use to aerospace applications with upper temperature limits below 170°C. It is stated, however, that water absorption by the epoxy resin - based matrix and adhesive systems impairs the allowable matrix strains and lowers the heat distortion temperatures of the resin. Moisture absorption is, however, considered to be a minor problem, i.e. it can be designed around, or eliminated through modification of, or addition to, the basic resin molecule.

Lockheed comment that the critical temperature as far as moisture absorption is concerned is about 93°C. A particular fin (L - 1011), operates at a maximum temperature of 71°C and problems are not expected to arise.

Self-reinforced polymers are discussed where high strength plastics might be obtained by orienting polymer molecular chains with respect to each other within the plastic itself. Current fabricating complexities would be circumvented and fibre-plastic interface problems eliminated. If this concept proves viable, it should be possible to produce a one-piece wing skin, as is now done with metal, without having to worry about putting fibres in and orienting them in specific directions. It is emphasised that the AF Materials Laboratory Non-metallic Material Division has only demonstrated that these kinds of polymers can be synthesised.

74 Brush, D R; Schulz, R B and Jorgensen, L: 'Initial magnetic permeability measurements of rf shielding materials', IEEE 8th EMC Symp. Record, 1966, First paper of Session 4A (no page numbers).

This paper contains material to be found in Ref.45.

75 Stirrat, W A: 'USAECOM contributions to shielding theory', IEEE Trans. on EMC, Vol.EMC-10, No.1, March 1968, pp.63-66.

This paper presents a circuit approach to shielding using a transmission line analogy. A shield is represented as an inductor and the currents induced in it by one point source on the exciting aerial can be multiplied by the number of point sources of the aerial producing the same effect. Equations available from references can be used to calculate the shield's inductance from its geometry. A value for the effective inductance of a flat infinite shield is also obtainable.

76 Gill, R M: 'Carbon-fibres in composite materials', ILIFFE Books, London, 1972 (published for the Plastics Institute, London, SW1).

After giving a substantial amount of information concerning the origins of fibre reinforcement techniques and the selection of materials the production of carbon-fibres from cellulose, polyacrylonitrile and other materials is described.

Theory and measurement are largely concerned with mechanical properties of composites. Electrical properties are not dealt with to a significant extent.

The fina. section of the book is concerned with applications and market growth prospects for CFC materials.

Apart from theoretical treatments, manufacturing processes and measuring techniques, the book is a useful source of information, regarding proprietary materials, patents and areas in which CFC is likely to come into use.

77 Pike, R A; Douglas, F C and Wisner, G R: 'Electrical dissipation factor: guide to moulding quality graphite/resin composites', Polymer Eng. & SCI, Vol.11, No.6, November 1971, pp.502-506.

Copper foil plates are attached to the composite prior to curing. These plates are insulated from the composite to prevent the conductivity of the graphite from effectively short-circuiting the capacitor formed by the plates. It appears that the loss factor of the resin matrix alone is obtainable by this means. Its variation during cure (temperature and

pressure varied), allows the state of cure to be monitored. The point at which pressure is applied can be regulated, so minimising the production of voids in the matrix.

78 'Audrey Automatic Dielectrometry', Product Bulletin of Tetrahedron Associates Inc., 7605 Convoy Court, San Diego, California 92111, USA.

Bulletin not available for comment, but Ref.77 refers to this equipment in the monitoring of changes in dielectric properties during processing.

79 Dauksys, R J and Ray, J D: 'Properties of graphite fibre non-metallic matrix composites', J Compos. Mater, Vol.3, No.4, 1969, pp.684-698.

The mechanical properties of carbon fibres and yarns and tows are described, together with photographs of cross-sections of fibres from a number of manufacturers viz. Thornel (Union Carbide); HMG types (Hitco); Great Lakes; Morganite; HM HT (Courtaulds).

Thornel and HMG are shown as crenulated, Morganite and Courtaulds as circular and GLCC as crenulated, irregular or dog-boned in cross-section.

The data given in this paper were obtained from composites using Union Carbide epoxy resin ERL2256.

80 Donovan, P D and Watson-Adams, B R: 'Formation of composite materials by electrodeposition', Metals and Mater, Vol.3, No.11, 1969, pp.443-450.

Nickel plated carbon fibres are used to produce composite materials by compacting and sintering aligned bundles of these fibres. A suitable nickel plating bath is described.

81 Weeton, J W: 'Fibre metal matrix composites', Mach Des., Vol.41, No.4, 1969, pp.142-156.

The production of fibres is described, e.g. by whisker growth, glass drawing, wire drawing, vapour deposition, precursor technique etc.

Boron in aluminium, steel in aluminium or tungsten in copper and many other combinations are discussed. Such composite materials may even be used in structural parts of aircraft as well as for engine components.

82 Perry, J L and Lloyd, K J: 'Current flow phenomena in boron and graphite fibre reinforced composites exposed to simulated lightning', Lightning and Static Electricity Conference, Report AFAL-TR-72-325, December 1972, pp.294-305.

Similar content and conclusions to those of Ref.63.

83 Fisher, F A: 'Electromagnetic properties of composite materials', Lightning and Static Electricity Conference, December 1972, pp.306-314.

Pulsed and CW measurements of shielding factors for boron-epoxy and graphite-epoxy composites are described. CW was found to yield more useful data. A measurement technique described by Eckersley* was employed. Magnetic shielding was measured by inserting small samples, (13" diameter or 6" x 12" rectangular), between a pair of electrostatically shielded coils at frequencies from 0.5 MHz to 20 MHz. 17 dB of attenuation was observed with 0.04" CFC. Panel orientation and ply lay-up did not affect test data. (No edge contact provided on panels, however).

*See Ref.84.

84 Eckersley, A: 'H-field shielding effectiveness of flame-sprayed and thin solid aluminium and copper sheets', IEEE Trans. on Electromagnetic Compatibility, Vol.EMC-10, No.1, March 1968, pp.101-104.

Aluminium, when sprayed using an oxy-acetylene flame, was shown to be inferior in shielding qualities to aluminium foil. The screening to weight ratio was seven times worse for sprayed aluminium relative to foil, although the aluminium oxide content of the former was low. The author notes that flame-spray techniques other than oxy-acetylene exist. The measurement involved the insertion of small samples of coated insulation board between transmitting and receiving inductors.

85 Force, R; Geren, P; Strawe, D and Schmidt, A: 'Investigation of effects of electromagnetic energy on advanced composite aircraft structures and their associated avionic/electrical equipment', Phase 2, Vol.1, Report D180-20186-4, The Boeing Company Final Report, September 1977.

Prepared for Naval Air Systems Command, Dept. of the Navy, Arlington, Virginia 20306.

After a lengthy introduction and programme overview some results are presented for conductivity at 1 kHz involving 4, 16 and 32 ply laminates. Edge to edge, surface and volume resistivities are presented.

Resonant cavity techniques at 9 GHz were ineffective in assessing resistivity as fields did not penetrate the material sufficiently.

A shorted waveguide method with and without specimen placed in front of the short (at 8 to 12 GHz), showed the specimen to be indistinguishable from a short. Again, fields did not appreciably penetrate the sample.

A waveguide transmission test was tried next but rf leakage around the periphery of the specimen rendered the measurements invalid. Attempts are to be made to remedy this defect.

An anechoic chamber method is then described with a transmitting aerial inside the latter. A test specimen was electrically connected to one end of the chamber and a receiver horn was placed directly on the outside of the specimen. RF leakage difficulties arose and were reduced by the application of copper sealing tape and microwave absorber material. Measurements covered L-band (1 to 1.7 GHz) and X-band (8 to 12 GHz). RF conductivity may be calculated from measured loss data and for 4 ply (0, ±45, 90^o) material is 1.9 x 10^4 Sm^{-1} at 2 GHz and 0.9 x 10^4 Sm^{-1} at 10 GHz. RF conductivity was found to be thickness dependent. No rf bulk conductivity measurements are presented in the range 1 kHz to 1 GHz.

Surface conductivity measurements are stated to be in progress from d.c. to 1 GHz. Parallel plate techniques, where the plates are constructed from CFC materials, are to be used.

Data given for shielding effectiveness at frequencies above 1 GHz is stated to be at variance with corresponding measurements given under Ref.69 above, where such shielding effectiveness was said to be independent of sample thickness.

CFC woven cloth is regarded as important constructional material for which rf data is required.

Lightning and nuclear EMP induced effects are discussed and various aircraft configurations and models are considered. Static and weapon-generated electromagnetic energy threats receive examination.

Aspects of aircraft systems such as grounding, power, weapons and stores are considered.

An analytical model for aerial pattern coverage is given and measurements obtained for a 15.5 GHz slot aerial mounted on a 32 ply composite panel. Further measurements with $\lambda/4$ monopoles were conducted at frequencies down to 1.6 GHz. The measurements are said to indicate that significant pattern degradation only occurs for systems operating in Ku band. It is pointed out, however, that rf aerials in general and especially the hf notch design have very low radiation resistances and required low resistance bonds and high conductivity materials in the vicinity of the notch. Additionally the whole airframe is required to radiate at these frequencies and aerial efficiency is at risk.

The report concludes with an assessment of structural aspects of the use of composite materials in airframes.

86 Hanson, A W: 'A review of work on carbon fibre composites, Part 1', CLSU Memo No.66, Culham Laboratory, June 1978.

It is suggested in this report that differing experimental techniques may account for at least some of the differences in results for resistance obtained by various workers. Bulk resistance measurements are prone to errors where techniques have not made an adequate allowance for the effects of interfaces at the end connections. Non-linear effects have been reported in CFC materials at high current densities, but work at CLSU and by King and Amason suggests that non-linear effects occur principally at joint interfaces.

The review notes work that suggests an absence of skin effect in some composite materials, but as it is difficult to see how this can occur in view of fibre connections at the ends and fibre to fibre connections within test samples, it is suggested that investigations using alternative techniques would be appropriate.

Effects of fibre orientation and the current carrying capacity of CFC materials are discussed. For pulsed currents the parameter $\int i^2 dt$ appears to be the most important.

Interfaces, metal to CFC and CFC to CFC are considered. Compression joints employing bolts, rivets etc. can be employed and countersunk titanium screws have given good results.

Moulded-in metal components can be successful if dimensions are suitable and manufacturing techniques can be controlled.

Metal components glued to CFC can present problems where a fairly high level of insulation arises at the joint.

Plated or vacuum deposited joints can be produced but are difficult on large components and compatibility problems may occur.

Little work has been done on CFC to CFC jointing but investigations should proceed on lines similar to those appropriate to other interfaces.

87 Hanson, A W: 'Direct effects protection methods for thin skins/composites', NATO Air Electrical Working Party, September 1978, pp.22-1 to 22-3.

This paper notes the increased hazard in CFC due to heat damage and delamination at all interfaces and joints resulting from the direct effects of lightning current. Surface damage and delamination can be avoided by the use of thin metal protecting ablation layer.

88 Yates, B and Wostenholm, G H: 'Electrical conduction in carbon fibre reinforced composites', Department of Pure and Applied Physics, University of Salford M5 4WT. (Report of work carried out under RAE Order No.LSC/D/21681.

Investigations into the electrical resistivity of specimens of a unidirectional CFC were made in the direction parallel to the fibres between about 80 and 415°K. In directions of 45° and perpendicular to the fibres the measurements were extended to about 465°K. Attention is drawn to the directional sensitivity of the resistivity and its temperature dependence. Absolute values of resistivity at room temperature were obtained using indium end contacts under moderate pressure.

89 'Report of Composite Material and Metal Composites Joint Workshop', Naval Air System Command, US Department of the Navy, 24 and 25 August 1978.

This is an assembly of copies of viewfoils presented at the meeting and the discussions are not reported.

Birken, J: 'Overview of joints in composite materials', Naval Air Systems Command.

Viewfoils show aircraft including AV-8B and indicate coupling mechanisms and coupling analysis procedure for NEMP. NEMP is compared with lightning. A table of electric properties for composites indicates longitudinal conductivity for graphite-epoxy as 2×10^4 Sm^{-1} and permittivity as indeterminate.

A summary of formulas for shielding effectiveness relates this quantity to fundamental properties and source type (e.g. plane wave; loop, near-field; electric dipole, near field).

Magnetic shielding versus frequency is compared for seven layer graphite-epoxy overlay and aluminium over the frequency range 1 kHz to about 10 GHz.

Surface impedance Zs for composites, coatings and coated composites is given for frequencies from 10 kHz to 100 MHz.

Tables of peak transient voltages and current for lightning and NEMP are also given.

Skirt, rivetted and double staircase joints are illustrated with admittances 2, 15 and 230 Sm^{-1} respectively over the frequency range 0 to 100 MHz.

More complex joints are described with particular applications in mind e.g. skin splice at longeron or spar cap; typical wing stepping joint, etc.

From other viewfoils it appears that EMI test set-ups were discussed. The quadraxial method of measuring shielding effectiveness of tubular samples of CFC was described including the structural joints for the test specimens.

Shielding effectiveness test methods shown in a number of viewfoils included H-field tests using a CFC sheet as a partition in a screened box, E-field shielding by a cylindrical sample and some techniques for examining performance of joints in CFC. Waveguide and stripline methods were proposed for some tests on joints.

Gajda, W: 'Materials preparation, measurements and experimental set-up at Notre Dame'.

Viewfoils were shown indicating methods for measuring permeability and conductivity. Permeability is obtained using a permeameter comprising an electromagnet and balance. Conductivity involves the evaporation of aluminium on to the ends of a rectangular sample followed by an application of conductive paint to provide mechanical protection. Samples are typicall 60 mm x 4 mm x 1 mm. Measurements were made from 0.5 MHz to 50 MHz and conductivity decreases with increase in frequency.

A table shows relative permeability as unity and relative permittivity as indeterminate for graphite-epoxy composite. Longitudinal conductivity is given as 2×10^4 Sm^{-1}, transverse conductivity is given as 100 Sm^{-1}.

Conductivity enhancement by diffusion from gases in a furnace was illustrated for both graphite and boron. For graphite, post-diffusion to pre-diffusion electrical conductivity ratios up to about 50 are indicated on a graph.

Wallenberg, R: Syracuse Research Corporation.

Viewfoils representing diffusion, surface transfer impedance, magnetic shielding effectiveness, electric shielding, joint admittances were shown. Aperture problems and network equivalents were also shown as viewfoils.

Carri, R: Grumman Aerospace Corporation.

Multiple threats stated i.e. lightning static electrification, electromagnetic interference as operational threats and high energy laser, NEMP as combat threats.

The distribution of lightning strike points was given.

NEMP effects were listed. External effects where surface changes are induced on aircraft. Penetration of aircraft by diffusion through skin, aerials designed to pick up the energy and inadvertent penetrations.

THREDE, a mathematical model was presented and worst case cable responses listed.

A viewfoil listing fibre properties and availability was shown.

Costs and weight factors for popular protection systems e.g. aluminium alloy flame spray were compared.

Structural fasteners were similarly examined. A total of 16 graphite/epoxy laminates were listed for plies, lay-up, conductivity etc.

Magnetic and electric shielding test methods were described and results given from 20 kHz to 1 GHz for tightly joined parts. Plane wave shielding effectiveness was also given for the range 100 MHz to 10 GHz.

Reardon, J P: 'Development of electrically conductive graphite-fibre reinforced composites', NACM/TSCC Program Review Paper C-11, 13-15 June 1978.

A NAVAIR sponsored programme is to develop highly conductive graphite-fibre for incorporation into composites. One or two plies of fibre of high electrical conductivity may provide greatly enhanced shielding. A highly graphitised pitch-base fibre developed by Union Carbide is suitable for this purpose. The inherent high conductivity of this fibre can be further increased five to tenfold by forming stable intercalation compounds. Conductivities about one tenth that of aluminium have been achieved. It is recognised that the need for long-term chemical stability may preclude adoption of some intercalants. Two intercalation compounds which are suggested are antimony fluoride and iodine chloride.

Note: Antimony fluoride (SbF_5) is a Scheduled Poison S1.

Tomkins, S S: 'Alternate composite materials to minimise the possible carbon fibre electrical hazard', Materials Division, NASA Langley Research Center, Hampton, VA 23665.

Modifications are proposed where, for example, intercalation of graphite fibres, glass, carbide and organic coating may be adopted.

Matrix materials may be evolved, new fibres e.g. organic boron nitride. This group appear to be involved in increasing the electrical resistivity of graphite fibres without degrading mechanical properties. Resistivity of GY-70 and P fibres has been increased by 900 times. Fibres have also been increased in resistance by 10^6 times by coating with SiO_2.

Swink, D: NSWC/Dahlgren.

Viewfoils list measurement techniques, i.e. 'Mode-stirred chamber giving shielding effectiveness'. 'Contact impedance giving material/joint model'. Face-to-face measurements made using vector impedance meter.

Bechtold, G W; Hunter, P E and Libelo, L: 'EMP measurements of composite panels mounted on an aluminium cylinder', Work sponsored by Naval Air Systems Command.

Viewfoils list the requirements and methods of test i.e:

Tests in a 20 kV/m field produced by the NSWC simulator. The test object consists of an aluminium cylinder about 15" diameter and 16' high with a composite panel mounted on the surface. The internal H and E fields and current and voltage in an internal mounted wire were measured and comparisons were made with an aluminium panel and with no panel installed. The panel was layered as $+90^{\circ}$, -45°, $+45^{\circ}$, $0^{\circ}+45^{\circ}$, -45°, $+90^{\circ}$ and 10" x 10" x 0.038" in dimensions.

Composite shielding was found to be about 12 dB worse than aluminium at EMP frequencies. Composites were found to affect the frequency content of internal signals. It is claimed that composite joints can be evaluated at EMP frequencies using these techniques.

Donaldson: Georgia Institute of Technology.

Viewfoils of anechoic chamber etc. but no written material.

Cheng, D: University of Colarado.

One viewfoil depicting a coaxial system with aperture in outer CFC sheath. No written material but experiment may be concerned with screening offered by CFC with aperture.

Prehoda, Rom: NSWC/Dahlgren.

Viewfoils show coupling between aerials in shielded enclosure with equivalent circuit.

Contributors who did not provide viewfoils are listed below.

Stratton, R: Rome Air Development Centre.

Condon, G: General Electric.

Roden, J: Syracuse Research Corporation.

Skouby, C: McDonnell Aircraft Corporation.

90 Gajda, W J: 'A fundamental study of the electromagnetic properties of advanced composite materials', RADC-TR-78-158 Phase Report, Rome Air Development Center, July 1978.

It is noted that composite materials such as graphite/epoxy and boron/epoxy are inferior to metals in respect of degradation by lightning strike and screening characteristics. The electrical properties of composite materials could be improved by increasing fibre-to-fibre contact but it is pointed out that these materials are fabricated so as to minimise fibre contact and microbuckling. Attempts to increase conductivity by increasing fibre contact would lead to an unacceptable degradation in mechanical performance.

Electrical performance would be improved if fibre conductivity was increased without a significant fall in specific strength. Because density must not be increased, plating of fibres with metals is not considered suitable. Loading the composite with high permeability materials to increase overall permeability is equally unacceptable.

Doping techniques where dopants are added in parts per billion concentrations and result in orders of magnitude increase in fibre and composite conductivity may be feasible.

In order to investigate these possibilities, as a starting point ohmic contacts were made to fibres and conductivities measured at low frequencies.

Doped fibres were obtained by diffusing boron into graphite fibres and carbon into boron fibres under various controlled conditions. Conductivity of graphite was increased by a factor up to a maximum of 5.

The process of intercalation of graphite fibres was briefly investigated. Carbon fibres were immersed in a mixture of antimony pentafluoride and hydrofluoric acid in order to introduce superacid radicals into the basal graphite planes. Electrical conductivity was increased by a factor of 8 but fibres were found to be more prone to breakage after such treatment. Work was discontinued on intercalation experiments in view of the effort underway at the University of Pennsylvania and the Naval Research Laboratory.

91 Allen, J L; Adams, A T; Gajda, W J; Heintz, R E; Walker, W F; Graham, O and Erickson, J E: 'Electromagnetic properties and effects of advanced composite materials: measurement and modelling', RADC-TR-78-156, Phase Report, June 1978.

After a brief introduction this report contains five further sections numbered 2 to 6, by different authors. These are:

(i) Section 2 by W Gajda deals with methods for measuring the electrical properties of composite materials in the range d.c. to 30 (or 50) MHz.

Permeability of graphite/epoxy, boron/epoxy and Kevlar/epoxy was determined at d.c. and 60 Hz. All three materials were found to be weakly diamagnetic with magnetic susceptibilities about 10^{-7}. The low frequency permeabilities of these materials are essentially equal to that of free space.

Permittivity of these three materials was measured over the frequency range 10 kHz to 50 MHz. The relative permittivities were found as 5.6 for boron/epoxy and 3.6 for Kevlar/epoxy. The permittivity of graphite/epoxy was concluded to be indeterminate over the frequency band investigated.

A conductivity model for current in the longitudinal direction using a volume fraction of fibre in the composite gave excellent agreement with some measurements on a sample.

A simple model for current in transverse directions was in error by a factor of 70. Analysis continues using more precise models.

In the case of multiple-ply samples a model is given which gives good agreement with experiment after numerical determination of longitudinal, transverse and 45° conductivity.

An investigation into the effects of absorbed moisture showed that no significant changes occurred in longitudinal conductivity. Transverse conductivity was found to increase and was consistent with the hypothesis that swelling of the epoxy resin reduces fibre-to-fibre contact. It was found, however, that the resistance of samples which had not been immersed in water was also increasing. This effect occurred only where rubbed indium-silver paint electrodes had been used. The water immersion test samples also had rubbed indium and silver paint electrodes.

Temperature effects were found to be small over the range $77^{o}K$ to $300^{o}K$ for multiple-ply non-directional samples (about 15% change in conductivity over whole temperature range).

(ii) Section 3 by R E Heintz and W F Walker deals with methods for measuring the electrical properties of composite materials in the range 30 MHz to 1 GHz.

Two methods of measurement of admittivity were investigated. One of these involved the measurement of the impedance of a small composite strip connected across a parallel-plate transmission line. Difficulties arose with uncertain contact resistance, inconvenient sample sizes and transmission line discontinuities.

An alternative method using a slotted stripline is described. A transmission line consisting of outer parallel aluminium plates with a flat centre conductor of composite material. The propagation constant $\gamma = \alpha + j\beta$ is determined by line geometry and the admittivity $Y_c = (\sigma_c + j\omega\varepsilon_c)$. γ is determined from standing wave patterns on the line and Y_c is calculated from γ.

The results from the parallel-plate tester could only indicate an approximate lower-band on conductivity of $>3 \times 10^{2}$ Sm^{-1} between 140 MHz and 1 GHz.

A simplified version of the slotted line (0.1 m in length), was constructed and a preliminary set of measurements indicate values of σ for unidirectional graphite/epoxy composite of $>3 \times 10^{4}$ Sm^{-1} in the direction of the fibres.

The strip-line method is stated to be most appropriate to the measurement of unidirectional samples of uniform fibre density. A further slotted line was used to measure the conductivity of a strip of unidirectional composite 0.23 m in length and a value of 1.9×10^{5} Sm^{-1} was obtained. This value is felt by the authors to be high by a factor of 3 or 4. This high value is thought to be due to low density of carbon fibres at the surface of the strip. This makes the effective dielectric spacing greater between inner and outer conductors. The effect could be reduced by removing the outer epoxy layer or increasing the dielectric spacing so that the effect of the epoxy layer becomes small.

(iii) Section 4 by J L Allen deals with the theory of shielding effectiveness.

Shielding theory and definitions are discussed in some detail together with surface transfer impedance and effective conductivity. Transmission loss and phase measurements by the use of flat plate samples mounted in a waveguide or transmission line structure are described together with theoretical treatments according to sample types.

(iv) Section 5 by A J Adams deals with numerical techniques for the analysis of the performance of composite materials. The basic change for the electromagnetic analysis is said to be the shift from lossless to dissipative materials.

Basic scattering problems are illustrated. Mechanisms for coupling energy to the interior of a composite body are shown as:

(a) penetration through the skin.

(b) coupling through apertures.

(c) coupling via aerials, etc.

Radiating properties of aerials on composite airframes and coupling between aerials on composite airframes are noted as problems.

Numerous references on specific problems and on numerical techniques are included.

(v) Section 6 by Captain J E Erickson and Lt Colonel O D Graham is based on a report to be published by these authors.*

Aerial characteristics obtained by measurements are shown, using both metal and CFC ground planes.

*Erickson, Capt J E; Graham, Lt Col O D; McCannon, Maj J D and O'Brien, Capt: 'Performance of graphite/epoxy as an antenna groundplane', To be published by the US Air Force Academy, Co.

92 Baskerville, M W: 'A short study of the anisotropic resistance in carbon fibre composites', Plessey Research (Caswell) Limited, September 1978.

The satisfactory performance of electroless copper plate on carbon fibres is noted. Rectangular pieces of unidirectional CFC material were examined for resistivity along and across the fibre direction and through the sample. Using these results and further measurements obtained for resistance between points at various angles to the fibre direction a basic theory describing the resistance of unidirectional CFC materials was evolved.

It is noted that the resistance between points along the fibre direction is almost entirely dependent upon the number of fibres mutually contacted, the size and shape of the specimen being unimportant. Resistance between points having no direct fibre connections is dependent upon the perpendicular distance between the bunches of fibres contacting each point and upon the lengths of the intervening fibres.

In multilayer material observed resistances in certain cases are lower than would be expected from simple theory where it is assumed that each layer is an independent unidirectional layer. The discrepancy is due to inter-layer conduction providing an alternative parellel path.

Suggestions are made for improvements to existing bonding techniques, e.g. metallisation of the interior of the drilled and countersunk screwholes, metallisation of the outer edges of plates, onto exposed fibre ends etc.

93 Rees, G J: 'Theory of conduction in carbon fibre composites', Plessey Research (Caswell) Limited, September 1978.

Models of CFC materials are considered. Where fibres in successive layers are oriented parallel, conduction parallel to fibre direction is high and perpendicular to the fibres is low. In the latter case conduction may go by circuitous routes via accidental points of contact or close approach of fibres.

Methods are outlined for calculating the resistance between two contacts to CFC with successive layers arranged parallel or perpendicular.

The resistance between contacts to a 'parallel' composite can be treated by solving a modified Laplace equation in a manner similar to that necessary for treating an isotropic conductor.

A 'perpendicular' composite can be treated as an isotropic two-dimensional conductor provided that the geometry of the problem is on a scale much greater than 70 mm. On this scale measured conductivities will be isotropic. Otherwise two coupled Laplace equations must be solved describing the potential in the two types of layer.

94 Whitney, J M: 'Moisture diffusion in fibre reinforced composites', Technical Report AFML-TR-78-42, Air Force Materials Laboratory, Ohio, USA, D of I TRC Report No.AD-A053 561, April 1978.

This report discusses the mathematics of moisture diffusion as applied to laminated fibre reinforced composites. Moisture absorption by epoxy resins is said to cause plasticization with swelling and lowering of the resin's glass transition temperature (temperature at which the polymer changes from a glassy solid to a rubbery solid). Because of this lowering of the transition temperature there is an interest in determining the mechanical properties of CFC at various temperatures in the presence of moisture. Theoretical results for moisture diffusion (weight gain) are compared with experimental data for graphite-epoxy composites and good correlation is found for both unidirectional and thick bidirectional laminate. The correlation for thin bidirectional laminate is only fair and it is speculated that this could be the result of a cracking phenomenon or stress dependent diffusion process associated with large residual stresses which are present in bi-directional laminates. Volume fraction was chosen as 0.6 and it is noted that actual volume fractions for graphite/epoxy laminates vary from about 0.6 to 0.65.

Experimental samples were fabricated from Hercule's AS/3501-5 graphite/epoxy pre-preg system, cut into small specimens, and exposed to equilibrium under various temperature and humidity conditions. Four-ply unidirectional, four-ply $(0.90)_s$ and twenty-ply $(0.90)_{5s}$ samples were produced. Humidity exposures included underwater, 95% and 75%. Temperatures included 38°C, 49°C, 60°C and 71°C. Exposure procedures were in accordance with those described by Whitney and Browning.*

*'Some anomalies associated with moisture in epoxy matrix composite materials', Environmental Effects on Advanced Composites, ASTM STP, American Society for Testing and Materials, Philadelphia, Penn., USA (To be published).

95 Evans, R H: 'Approximate calculation of direct current diffusion in multilayer CFRP panels', Unpublished paper, Engineering Physics Dept., RAE, Farnborough, 2nd revision, February 1979.

A three-layer strip of CFC material is represented by a network of resistors and a diffusion distance is calculated which defines the distance required for the current to diffuse to its final 'long-strip' distribution in which the current divides in inverse ratio to the resistances of the layers. Most practical strips are likely to be long in relation to this diffusion distance.

If R_1 is the resistance for unit length of the top (and bottom) layer, R_2 is the resistance per unit length of the middle layer, expressions are derived for the voltage drop along the top and bottom of the strip and for the voltage drop across the thickness of the strip for the conditions listed below:

(a) R_2 much larger than R_1. Long strip.

(b) As (a) but for a short strip.

(c) General value of R_2. Long strip.

The method is stated to give an approximate equivalent circuit representation of the flow of current in an isotropic medium having discontinuities in the value of resistivity (at the boundaries of the layers).

96 Pridie, R A: 'Environmental effects on composites for aircraft', NASA Technical Memorandum 78716, May 1978.

A number of environmental effects programmes are discussed and results given. Flight service experience over a 5 year period for 142 composite aircraft components is given and involves 1 million flight service hours. Ground-based outdoor exposure of samples for a period of 3 years is also described.

The composite materials used were combinations of graphite or aramid fibres and epoxy resins as listed below:

Thornel 300 graphite fibres (Union Carbide Corporation).

A5 graphite fibres (Hercules Inc).

Kevlar 49 aramid fibres (E I du Pont de Nemours and Co. Inc).

Narmco 5208 and 5209 epoxy resins (Narmco Materials, a subsidiary of Celanese Corporation).

2544 epoxy resin (Union Carbide Corporation).

3501 epoxy resin (Hercules Inc).

Hexcel F155 and F161 epoxy resins (Hexcel Corporation).

Conclusions are presented and include the following:

Residual strength tests of graphite-epoxy spoilers removed from service annually have shown no significant effects in four years.

Ground-based outdoor exposures of composite material samples after 3 years of exposure have reached equilibrium levels of moisture pick-up ranging from 0.5 to 2.1% of the composite laminate weight, and have produced a solar ultra-violet induced material loss for unprotected epoxy matrix specimens which is less than 25% of one ply. Specific levels of moisture pick-up are predictable and are dependent on the particular material system. No significant degradation occurred in residual strength tests of 3 year outdoor exposures worldwide for interlaminar shear, flexure and compression specimens; for stressed and unstressed tensile specimens; and for exposures to aviation fuels and fluids.

97 Sandorff, P E and Tajima, Y A: 'The experimental determination of moisture distribution in carbon/epoxy laminates', Composites, January 1979, pp.37-38.

Thin slabs of laminate were obtained using a laboratory microtome. A thickness of 0.25 mm was found convenient. The slabs were weighed immediately and then placed in a drying environment (1 to 3 days in vacuo at 93°C over anhydrous calcium sulphate). Higher drying temperatures are said to result in dehydrolysis and loss of other low molecular weight species, even with resins cured at 180°C. The weight loss for each slab was treated as an average value and plotted against slab median location. The latter was determined from the slab weights, for the k^{th} slab, the median location is:

$$\frac{\sum_{i=1}^{k-1} W_i + \frac{1}{2} W_k}{\sum_{i=1}^{n} W_i} \cdot h$$

where W_i is the weight of slab i after drying, n is the total number of slabs and h is the total (original laminate) thickness.

The method is stated to be a simple, fast and low cost method for the determination of the distribution of moisture through the thickness of a composite laminate. A rapid determination of the solubility and the diffusion coefficient is also possible.

98 'Carbon fibre fabric for high performance composites', Bulletin No.95, Fothergill and Harvey Limited, Industrial Textiles Division, Summit, Littleborough, Lancashire OL15 9QP.

Fibre specification and properties (resistivity is 1.6×10^{-5} Ωm), fabric construction details and comparative properties are given. Applications include wing-span for Jaguar aircraft. Cost is £85/kg for quantities of 50 kg and above.

99 'Carbon fibre hazard concerns NASA', Aviation Week and Space Technology, 5 March 1979, pp.47-50.

NASA is conducting a risk analysis programme concerning the effects of loose carbon fibres in electrical electronic equipment. Such fibres released during an accident to an aircraft involving fire or explosion may penetrate buildings and equipment enclosures and damage equipment. The programme is limited to accidental release of fibres from commercial air transport aircraft. It is not concerned with the problems of carbon fibre release from military aircraft as it might affect military operations.

NASA will let no more contracts for flight evaluation or production development of carbon/epoxy components for aircraft until a conclusive determination can be made of the hazard. The analysis will end in 1980.

100 Lee, K M; Perala, R A and Cook, R B: 'External EMP coupling to a composite aircraft', IEEE International Symp. Digest, Antennas and Propagation, USA, May 1978, pp.17-20.

It is noted that for metallic aircraft diffusion of EMP signal through the skin is unimportant but this may not apply for graphite-epoxy skins. The EMP induces surface currents and charges on the aircraft exterior which then couple signals via aerials, apertures, exposed cables and diffusion through the skin to the aircraft interior. The skin surface impedance Z_s is often assumed to be zero for a metallic aircraft and it is necessary to assess the value of Z_s for a composite skin which may include non-composite areas. A conceptual aircraft (ADCA) is shown and overlaid with a mathematical model (THREDE). Results indicate that no discernible differences for external coupling in response to an incident wave of double exponential form occur for skins having surface impedances between 0 and 1 Ω. The difference in peak current density is less than 6% for a surface impedance of 10 Ω. ADCA surface impedances are less than 1 Ω and it is concluded that for most practical cases the transient response of a composite aircraft is well approximated by that of a perfectly conducting one as far as the exterior problem is concerned.

101 Baker, A A; Harris, S J and Youdan, G H: 'Method for manufacturing coated or covered fibres', Patent No.1939339, Federal Republic of Germany, 3 August 1968, Applicant: Rolls-Royce Limited, Derby, UK.

This patent describes the coating of fibres with aluminium by the decomposition of tri-isobutyl aluminium (TIBA) in a furnace at a temperature of 260°C. A system for coating carbon fibres is shown as an example, and it is suggested that other organo-metallic vapours could be used to deposit metals such as nickel, iron, titanium etc.

102 Yamaki, J; Maeda, O and Katayama, Y: 'Electrical conductivity of conductive filler-polymer composites', Rev. Elec. Commun. Labs., Vol.26, Nos.3-4, March-April 1978, pp.616-628.

This is a theoretical study of the electrical conductivity of composites containing conductive short fibres or particles based on the probability of contact between the conductive fillers and conductive path in the composite. Some of the relations were compared with experimental values and the conclusions reached were as follows:

(a) Fibre composite conductivity increases with an increase in fibre length.

(b) The critical fibre content, where the conductivity rapidly changes, decreases with increase in fibre length.

(c) The fibre composite theoretical conductivity showed fairly good agreement with experimental values, if the apparent contact resistivity of fibres was chosen so as to fit the theoretical curve to experimental values.

(d) The apparent contact resistivity seemed to increase with increase in polymer-fibre adhesion strength.

(e) Conductivity dependence on composite strain was clarified theoretically and experimentally. Some possibilities exist to use the composite as a pressure-conductivity transducer.

103 Antoniu, S: 'Skin effect in steady state for a conductive bar with a rectangular non-homogeneous section', Rev. Roum. Sci. Techn.-Electrotechn. et Energ, Vol.20, Part 2, Bucharest, (In French), 1975, pp.147-159.

A study is made of the skin effect in a non-homogeneous conductive bar formed by three homogeneous layers, the outer layers being identical and having a smaller conductivity than the central one. The effect of the frequency of the a.c., of the relative thickness of the layers and of the nature of the constituent materials on the skin effect are studied especially with regard to the factors of increase of resistance and internal inductance of the bar under a.c. conditions.

A parameter $\beta_1 = 2D\left[\frac{\omega\ \mu_1 T_1}{2}\right]^{\frac{1}{2}}$ is defined, where D is the thickness of the outer layers and the other symbols have their usual significance. For values of β_1 which exceed 2, the skin effect is shown to be influenced almost entirely by the material of the outer layers of the bar. For a composite bar with outer layers of copper and a core of non-magnetic steel it is shown that the use of a mean value for d.c. conductivity does not give rise to significant errors in calculation. Errors in the calculation of the decrease in inductance with rise in frequency can be larger, however, if a mean value of d.c. conductivity is used.

104 'A report of observed effects on electrical systems of airborne carbon graphite fibres', NASA Technical Memorandum TM78652, US NTIS Microfiche Ref.N7815182, January 1978.

The release of carbon/graphite fibres into the environment is said to present a potential problem involving a hazard to electrical equipment rather than public health. The electrical conductivity of such fibres is the prime factor in their effects although other properties such as small diameter, general short length and low density are important contributing factors. The composite materials themselves pose no known hazards.

The samll size and low density of the fibres allow fibres to become airborne and to travel relatively long distances. Fibres can cause resistive loading, temporary shorts or electrical arcing. Almost all plants producing and using free fibres have experienced malfunctions of electrical and electronic equipment including, in some cases, resultant fires. Such problems have been limited by insulating bare conductors and installing fan filters. No problems have been experienced by industries receiving and using pre-impregnated fibres.

Burning of a composite material followed by mechanical agitation can release a fraction of the carbon/graphite as single fibres or as lint. Waste disposal by incineration represents a possible source of free fibres. Accidental fires in vehicles incorporating CFC materials are other potential sources.

Electrical equipment begins to be affected by fibres at a concentration of 10^4 to 10^7 (fibres m^{-3}) sec.

Research continues on this problem and it is suggested that disposal of CFC materials should be limited to controlled land fill.

105 Johnson, D: 'Bibliography on fibres and composite materials', Battelle Columbus Laboratories, Columbus, Ohio, USA, Metals and Ceramics Information Centre MCIC-78-38, US NTIS Microfiche Ref.AD A061903, 1972-1978.

This bibliography contains 463 references of which only a very small number are likely to be of relevance to CFC materials. These are listed

below with comments where an examination of the publication appeared useful - see Refs.106-116.

106 Corvelli, N: 'Design of bonded joint in composite materials', Proceedings of the Symposium on Welding, Bonding and Fastening Williamsburg Va, US NTIS Microfiche Ref.N74-30936, 30 May-1 June 1972.

This paper described the adhesive stepped bonded joint where the adhesive and composite matrix are co-cured. A design procedure is described along with the analysis technique upon which it is based. Comparison between analytical results and test results are shown. Electrical properties of these joints are not considered.

Note: Few of the papers presented at this Symposium are concerned with CFC material and none of these described electrical properties.

107 Hofer, K E; Rao, P M and Humphreys, V E: 'Development of engineering data on the mechanical and physical properties of advanced composite materials', Interim Technical Report, June 1971 - May 1972, AFML - TF-72-205 Part 1, Contract F33615-71-71-C-1713, AFML (Sept.1972).

US NTIS Microfiche Ref.AD - 757 524
Not examined

108 Olevitch, A: 'Development of engineering data on the mechanical and physical properties of advanced composite materials', Final Report June 1971 - May 1972, AFML TR-72-205, Part 1 Contract F33615-71-C-1713, AFML (Sept.1972).

US NTIS Microfiche Ref.AD-757524
Not examined

109 Rybal' Chenko, M K; Ustinov, L M and Zhamnova, V I: 'Electrical resistivity of fibre composites', Soviet Powder Metallurgy and Metal Ceramics, Vol.11, May 1972, pp.393-395.

Not available for comment.

110 Steele, J W; McCoy, J C and Frye, E R: 'Spiral wrap a technique for fabricating thick wall carbon composites', SAMPE Quarterly, Vol.4, No.1, October 1972, pp.1-15, (SAMPE = Science of Advanced Materials and Process Engineering).

The report describes the application of carbonized resin techniques for producing carbon filament reinforced composites and the development of ply orientations that minimize shrinkage stresses. The use of the method enables fabrication of thick-walled carbon composite shapes. The process is applicable to a variety of carbon and graphite filaments and test results are reported for several combinations.

Although this report is concerned with CFC structures which are carbonized by heating in an oven in order to withstand subsequent use at high temperatures, many details are included showing the use of prepreg matting in the construction of parts such as nose cones.

111 Albers, W and Philips, N V: 'Physical properties of composite materials', Proceedings of the Conference on in-situ composites, III - Physical properties, Report NMAB308-111, January 1973, pp.1-18.

Not examined.

112 Humphreys, V: 'Development of engineering data on the mechanical and physical properties of advanced composite materials', Sixth Quarterly Progress Report, Contract F33615-71-C-1713, March 1972.

Not examined.

113 Hilado, C J: 'Carbon composite and metal composite systems', Materials Technology Series, Technomic Publishing Co Inc, Westport Connecticut, Vol.7, 1975.

Not examined.

114 'Carbon fibre study', NASA Technical Memorandum TM-79449, 1977.

Not available for comment.

115 Chamis, C C; Lark, R F and Sullivan, T L: 'Boron-aluminium - graphite resin advanced fibre composite hybrids', Technical Note NASA TND-7879, February 1975.

This is a report of an investigation to determine the fabrication feasibility and potential of adhesively bonded metal matrix and resin matrix fibre composite hybrids. Electrical properties are not discussed.

116 Yermolenko, I N and Safonova, A M: 'Investigation of the electrical conductivity of carbon and metal-carbon fibres based on oxidised cellulose and its salts', Translation from Izvestiya Akademii Nauk Belorussky SSR, Report FSTC-HT-948-75 (1), August 1975.

US NTIS Ref.AD-B010814L (limited distribution)
Not available for comment.

117 Karr, P R and Smith, R A: 'Electrical properties of a lossy dielectric containing short randomly disposed metal fibres', 1979 International Symposium Digest on Antennas and Propagation, pp.612-615.

This paper considers the prediction of the conductivity σ and the dielectric constant ε of a lossy dielectric material (e.g. concrete), where the material is altered by the addition of a large number of short thin metal fibres homogeneously but randomly disposed.

Some measurements are described in which metal fibres about 25 mm in length were incorporated with concrete at a volume density of 1.8×10^5 fibres m^{-3}. This volume density is stated to be too high for accurate representation by the theory presented since touching and clumping are more likely with high densities. In addition the theory requires that a representative wire be surrounded by a sphere without including other wires within the sphere.

This treatment is not applicable to the usual forms of CFC material and its application to chopped strand CFC is doubtful.

118 Prakash, R: 'Non-destructive testing of composites', Composites (GB), Vol.4, October 1980, pp.217-224.

Non-destructive testing (NDT) techniques are described, including radiography ultrasonics, photometer, X-ray, diffractometer and acoustic emission characteristic under deformaton.

Eddy current techniques are also described where a non-circular probe is used to study variations in anisotropy and to determine the lay-up order.

119 Springer, G S and Loos, A C: 'Moisture absorption of epoxy matrix composites immersed in liquids and in humid air', Technical Report AFML-TR-79-4175, Final Report for period March 1979-September 1979, US NTIS Microfiche Ref.AD-A082159.

The moisture content as a function of time and temperature was measured for three materials. Tests were performed in diesel fuel, jet fuel, aviation oil, saturated salt water and distilled water. Humid air and saturated steam were also used.

120 Elber, W: 'A probabilistic analysis of electrical equipment vulnerability to carbon fibres', NASA Technical Memorandum 80217, US NTIS Microfiche Ref.N81-11113/0, October 1980.

This is an analysis of the statistical problem of airborne carbon fibres falling on to electrical components and includes the probability of multiple fibres joining to bridge a single gap. The statistics were also investigated by controlled experiments.

121 Stumpfel, C R and Weaver, C E: 'Measured carbon fibre exposures to malfunction for civilian electronic items', Memorandum Report ARBRL-MR-02943, US Army Armament Research and Development Command, US NTIS Microfiche Ref.AD-B047 351/2, March 1980.

A sample of 24 items was selected to represent the large population of electronic items found in the home and office. These were exposed to airborne carbon fibres until malfunctions developed or until high exposure levels were reached. The resulting mean exposures to malfunction are to be used to estimate the hazard presented by carbon fibres accidentally released by civilian aircraft crashes.

122 Paszek, J J; Davis, D D and Patrick, J H: 'Carbon fibre transfer functions through filters and enclosures', Memorandum Report ARBRL-MR-02946, US Army Armament Research and Development Command, US NTIS Microfiche Ref.AD-E048 811/4, March 1980.

Experimentally determined values for the transfer of carbon fibres through air filters and electrical equipment cabinets are given together with a description of an improved technique for measuring carbon fibre exposure. The data shows that even coarse filters greatly reduce the transfer of carbon fibres.

123 Wright, W W: 'The effect of diffusion of water into epoxy resins and their carbon-fibre reinforced composites', Composites (GB), Vol.12, No.3, July 1981, pp.201-205.

The rate of water pick-up and the total amount absorbed are governed by the chemical structure of the resin and the cross-linking agent together with temperature and relative humidity. The absorbed moisture causes dimensional changes, generates internal stresses and results in reductions in the heat distortion temperature and certain mechanical properties at elevated temperatures. This paper surveys these effects.

124 Davis, G L and Vogel, F L: 'Electrical conductivity of intercalated graphite fibres and organic matrix composites made therefrom', Addendum to AGARD Conference Proceedings No.283, Lisbon, Portugal, 1980, pp.D-27 to D-32.

High electrical conductivity in carbon fibres is produced by intercalation with substances such as arsenic pentafluoride. Improvements in conductivity of several orders of magnitude are said to be possible for composites incorporating such fibres with the structural properties largely unaffected.

Questions relating to this paper are to be found on Page D-26 of these Conference Proceedings. Toxicity hazards, corrosive effects and deleterious effects on insulants were queried (ERA Technology Limited). The author replied that the arsenic content was 2% to 3% and a hazard could arise in a fire or crash.

Corrosive effects did not occur with Monel alloy but the effects with titanium were at present unknown. No harmful effects on cable sheaths or insulants were expected.

125 . Kalnin, I L: 'Intercalated graphite fibre conductor', Technical Report for US Army Mobility Equipment Research and Development Command, Ft. Belvoir Va, USA, NTIS Microfiche Ref.AD-A094405, Final Report for Period 26 September 1979-15 December 1980, (Author is with Celanese Research Company, NJ, USA).

Lightweight electrical conductors were developed from graphite fibres intercalated with highly electrophilic intercalants. Conductance increases of 30-36 times over the unintercalated fibres were observed. This corresponds to about 45% of the specific conductivity of copper at room temperature. Unlike copper, the intercalated graphite fibres exhibit a nearly zero temperature coefficient of conductance. The intercalated yarn did not change its resistance during 100 hours of passage of current at

1 W power dissipation and current densities of 25-35 A/mm. Four graphite 'wires', equivalent in size to 17-20 were delivered.

126 Ramohalli, K: 'Process modifications for improved carbon fibre composites: alleviation of the electrical hazards problem', JPL Publication 80-56, NASA Jet Propulsion Lab., NTIS Microfiche N80-33494/9, 15 June 1980.

This report describes attempts to alleviate through fibre gasification CFC electrical hazards during airplane-crash fires. Thermogravimetric (TGA) and differential scanning calorimetric (DSC) experiments found several catalysts that caused fibres to combust when composites were exposed to test fires. An important synergistic effect among catalysts was also demonstrated.

State-of-the-art and modified composites were tested in the 'Burn-Bang' apparatus developed by Ames Research Center, and in a high-voltage electrical detection grid apparatus developed by JPL. In a standard three-minute burn test the modified composites released no fibres, while the state-of-the-art composites released several hundred fibre fragments.

Techniques were pursued to decrease the approximately 10% mechanical-property deterioration accompanying catalytic treatment. Additionally, studies compared expected service life with and without catalytic modification, and electron microscopy and X-ray microanalysis furnished physical-appearance and chemical-composition data. Furthermore, an acrylic acid polymer fibre coating was developed that wet the carbon fibre (T300) surface uniformly with the catalyst, providing a marked contrast with the uneven coats obtained by solution-dipping. Also, studies at Pennsylvania State University yielded important data.

Several promising new concepts resulted from the project, including catalytic elimination of carbon particulates from Diesel exhaust, catalytic improvement of coal combustion, and electrical destruction of carbon particulates in combustion systems in general.

127 Volpe, V: 'Estimation of electrical conductivity and electromagnetic shielding characteristics of graphite/epoxy laminates', J. Composite Materials, Vol.14, July 1980, pp.189-198.

This paper presents experimentally verified analytical expressions to estimate the basic electrical conductivity and electromagnetic shielding characteristics of bare and protected graphite/epoxy laminates. These expressions can be used to compare the electrical performance of various configurations of graphite/epoxy laminates and candidate protective coatings that will improve the shielding characteristics.

D.C. resistance measurements were made on Hercules AS/3501-5A panels. From these measurements an empirical expression was obtained to estimate the electrical conductivity of any laminate composed of the (0/90/±45) degree family along the 0/90/±45 degrees directions.

Specifically,

$$J_L = C\left(L + N/2\right) N_T \quad \text{where}$$

J_L = The electrical conductivity along the desired direction in mhos metre^{-1}.

C = Electrical conductivity of a unidirectional, 0°, laminate, 35.10^4 mhos m^{-1} for AS/3501-5A.

L = Number of layers in the desired direction.

N = Number of layers in the $\pm 45^\circ$ orientation from the desired direction.

N_T = Total number of layers.

On the assumption that for screening calculations the material may be treated as electrically homogeneous shielding effectiveness S.E. is calculated as:

$$SE = A + R_1 + R_2 \quad \text{where,}$$

A = Absorption loss.

R_1 = Reflection loss at the shield boundaries.

R_2 = Correction factor due to reflections from the far boundary of the shield.

Magnetic, electric and plane wave calculations are described and experimental results are shown for magnetic field effectiveness which are in good agreement with calculation.

It is suggested that caution should be observed in using the shielding equations to determine the shielding capability of advanced composite structures on an aircraft immersed in an electromagnetic field. Procedures for the latter are said by the author to require the solution of Maxwell's electromagnetic theory equations to determine the induced currents and charges on the surface of the aircraft which in turn will induce currents and voltages on cables or other circuits inside the aircraft.

128 Adams, A T; Chang, C and Liu, T H: 'Radiation and scattering problems involving advanced composite materials', IEEE EMC Symp., 1980, pp.138-142.

Techniques are described for the treatment of radiation from antennas mounted on advanced composite structures. Resistive wire-grid and surface models are used to represent the composite materials. Results are presented.

It is noted that antenna efficiency is 100% for conductivity T = 0 and ∞. There must be, therefore, at least one minimum between these limits. This is said to occur approximately, when T corresponds to a ground plane resistance of 377 Ω per square. Antenna efficiency is also affected by the electrical dimensions of the antenna and the resultant antenna Q. It is pointed out that antenna efficiency of a monopole over a composite ground plane is greatly improved by adding a small metal sheet in the vicinity of the attachment point.

129 Allen, J L: 'Electromagnetic shielding effectiveness for isotropic and anisotropic materials', RADC-TR-81-162, Phase Report, Rome Air Development Centre, NY, USA, June 1981.

'ABCD' and 'Scattering' matrix analysis techniques for determining shielding of isotropic and anisotropic multilayered shields are presented. These techniques are claimed to be well-suited to computer implementation. A variety of materials fit the models used including advanced composite materials (e.g. fibre-reinforced epoxies where the fibres are 'long' and 'oriented'), conductive filled thermoplastics (random oriented chopped

fibres or other conductive particles) and the more common metallic shields. Whilst advanced composite materials are now widely used as structural and surface components in aircraft and spacecraft, chopped-fibre structural foams are used as enclosures for electronic equipment. Such applications are said to require accurate assessment of electromagnetic shielding effectiveness.

The author states that given the appropriate intrinsic material properties as input, computer simulations yield surface transfer impedance and shielding effectiveness in good agreement with experimental data. The programs can also be used to infer intrinsic material parameters given measured surface transfer impedance and/or shielding effectiveness data.

It is also noted that from reported measurements on advanced composite material it is apparent that the major shielding problem associated with these materials arises from seams and joints.

130 Brewster, D C and Patrick, P: 'Theoretical study of the electromagnetic properties of CFC', Report MTR.80/98, GEC-Marconi Electronics Ltd, Chelmsford, Essex, 1980.

This report describes measurements on the shielding properties of a CFC cone 2 m in length. These measurements were made to validate theoretical calculations described in the report dealing with non-planar CFC objects. (Earlier reports by Brewster dealing with the theoretical analysis of the electromagnetic properties of carbon fibre laminates are:

Part 1, MTR 79/115, Part 2, MTR 79/119; Part 3, MTR 79/107).

The incident field used in the present work was from the EMP simulator at RAE, Farnborough.

Comparison between theory and experiment based on an EMP of peak field 10^4 V m^{-1} showed that the shielding behaviour of CFC (for a particular lay-up and configuration could be predicted to within 6 dB. The work lent confirmation to the view that CFC does not have any unexpected behaviour in the frequency range 0-100 MHz.

The largest currents (several amps) arose when the internal line was earthed to the cone and distant from the cone axis. In this configuration the internal line is responding to a low frequency incident magnetic field against which CFC can be a poor shield.

131 Brewster, D C: 'Theoretical calculation of rf properties of carbon fibre laminates', AGARD Conference Proceedings CP-283, Lisbon, 1980, pp.5-1 to 5-16.

A single lamina of CFC was modelled as a homogeneous anisotropic conducting material. The infinite CFC sheet is then modelled as a sequence of laminae, each with the conductivity tensor orientated in a direction depending on the fibre direction. The shielding of a plane wave (0-1 GHz) was calculated for a plane wave incident normally on the infinite sheet. An estimate was made of the effect of a thin aluminium coating on shielding performance.

Effects on antenna performance were examined and the variation of apparent resistivity with frequency was calculated and compared with experimental results obtained at ERA (Ref.132).

A much simpler model of a CFC was also considered using an averaged conductivity tensor across all the individual laminae. The simpler theory was generally valid below 30 MHz.

132 Bull, D A; Jackson, G A and Smithers, B W: 'R.F. resistivity and screening characteristics of CFC materials', AGARD Proceedings CP-283, Lisbon, 1980, pp.6-1 to 6-21.

Investigations are described to determine the electrical resistance characteristics and screening properties of CFC. Resistivity was examined from dc to 300 MHz and certain environmental effects were noted under dc test conditions. The measurement of screening properties required much larger samples and test frequencies ranged from 150 kHz to 30 MHz for the magnetic mode and from 50 MHz to 1000 MHz for the electric mode.

It was found that skin effect for current flow occurred in manner similar to that for a homogeneous isotropic material. CFC panels were found to be inherently capable of providing high attenuation in the vhf band and higher frequencies. In the hf band the attenuation of magnetic fields is unlikely to exceed 20 dB at frequencies below 1 MHz. The importance of bonding the CFC panels to the main structure was demonstrated.

Magnetic field attenuation measurements in the range 150 kHz to 30 MHz were found to be substantially independent of source to panel distance, i.e. near and far-field sources give similar results.

133 Thomson, J M and Evans, R H: 'The UK Ministry of Defence programme on the electromagnetic properties of CFC', AGARD Conference Proceedings CP-283, Lisbon, 1980, pp.10-1 to 10-9.

Table 1 in this paper lists the UK MOD programme on CFC properties and shows organisations such as Plessey Ltd, MRL, CLSU, University of Salford, ERA and RAE itself to be deeply involved.

RAE Materials Department pioneered the development of CFC and its electrical properties came under examination at an early stage. Aspects such as lightning strike vulnerability, resistivity, non-linearity bonding aerial performance, shielding effectiveness and mathematical modelling have all come under examination. It is noted that the UK aerospace industry has also undertaken a sponsored work as at BAe Warton (resistivity measurements, system studies, electrostatic charging, lightning effects) and WHL Yeovil (shielding effectiveness). Close liaison has been maintained between all parties and an advisory group meets twice-yearly.

Some parts of the work are discussed in greater detail together with conclusions and future developments of the programme. It is noted that problems with CFC are not likely to inhibit their use provided that there is close liaison between the specialists in various aspects of design and materials.

134 Brettle, J; Lodge, K J and Poole, R: 'The electrical effects of joints and bonds in carbon fibre composites', AGARD Conference Proceedings CP-283, Lisbon, 1980, pp.9-1 to 9-17.

Dry compression joints, bolted joints and adhesively bonded structures were all investigated in the course of this work. Their electrical properties were examined from dc to 50 MHz and at certain higher frequencies.

Methods of reducing joint impedance are proposed and subjected to tests. Joint impedance has been found to alter permanently by the passage of current through the joint and a possible mechanism is suggested. Radio frequency intermodulation products are not significant unless bare cut edges touch.

It is concluded that joints in CFC are not good electrically at dc and low frequencies. Pre-treatments with bolted joints can improve performance

but protection from environmental effects by using sealants would be necessary. Adhesive joints can be improved electrically but not to the same extent as bolted joints.

135 Barton, G and MacDiarmid, I P: 'Aircraft manufacturers approach to the EMC/Avionics problems associated with the use of composite materials', AGARD Conference Proceedings, Lisbon, 1980, pp.12-1 to 12-23.

Detailed examples are given of the approach adopted by UK aircraft manufacturers to EMC/Avionic problems associated with the use of CFC.

For Jaguar CFC panels, lightning strike and rf effects (possible deterioration in shielding performance) were given special consideration.

The stages of failure due to lightning strikes are discussed and the test procedures adopted regarding simulation of such events are described in detail. Various types of panel were tested including SRBP and plain aluminium for comparison purposes.

RF shielding was investigated by comparing EMC clearance performance when CFC panels were fitted,with the performance obtained using metal panels.No significant degradation was introduced by the introduction of these CFC panels.

Composite rotor blades were subjected to lightning strike tests and a great deal of information was obtained leading to improvements in protection.

The conductivity of CFC for dc was investigated and theoretical treatments applied. The results showed that an airframe built exclusively of CFC could not be used as an earth return. If longitudinal structural members were retained in aluminium alloy the weight penalty could be small and these could be used as earth returns. It is concluded that bonding is seen as still in need of a satisfactory solution.

136 Kalnin, I L and Goldberg, H A: 'Intercalation and properties of high modulus graphite filaments intercalated with strong acceptors', Synthetic Metals, Vol.3, 1981, pp.159-167.

The electrical conductance enhancement and the weight change of high modulus graphite filaments were measured during intercalation at 23°C to 110°C with gaseous or liquid SbS_5. A_sF_5, HSO_3F, and combinations of

of these. With excess intercalant the intercalation proceeds monotonically to about Stage I accompanied by an up to 50 times increase in filament conductance and 100-300% gain in fibre weight depending upon the nature of the intercalant. Combinations of successive treatments with two intercalants were used to modify and optimise the intercalation kinetics. The addition or fluorine to the fluoride intercalant accelerates the intercalation, but is detrimental to the electrical conductivity.

137 Heckman, R V: 'Experimental modelling of laminar composites for multifrequency eddy current measurements', Bendix Report BDX-613-2482, Prepared for US Department of Energy under Contract DE-AC04-76-DP00613, 1976.

This report describes a computer modelling program originally developed by Dodd and Deeds of Oak Ridge National Laboratory capable of calculating the experimental voltage amplitudes and phases which can be obtained with rectangular cross-section coils being operated at multiple frequencies. This program was applied to two multilayered composites in order to determine the feasibility of making thickness and resistivity measurements of the individual layers. The results of these calculations indicate that the thickness of the aluminium/Kapton composite layers could be measured to a precision of better than one per cent and the resistivity of the conductive layers could be measured to a precision of better than ten per cent. The second composite, a structure consisting of alternating layers of aluminium and polyimide,a varnish, was found to be measurable also. A minimum of two frequency components were found to be necessary for the aluminium/Kapton composite while three frequencies were found to be necessary for the aluminium polyimide case.

138 Moreton, R : 'Electrical hazards due to the release of carbon fibres into the atmosphere'. Report MRCC/79/44, RAE, Farnborough, Hants. 1979.

It is noted that carbon fibres which were incinerated at a manufacturing site caused short-circuits at power sub-stations half a mile away and problems persisted in the area for 48 hours. Although fibres in a matrix could be less hazardous, free fibres are likely to result after an accident and fire in a composite carbon fibre/epoxy airframe.

American work is noted (Dahlgren Laboratory of the US Navy) where CFC sheets were burnt or subjected to explosions. A 15 - 20% release of fibres was obtained if burning was followed by an explosion. Burning followed by impact from a 1.7 kg weight falling through 4.6 m (NASA Laboratory) released less than 0.1 % of the fibres.

Tests at a China Lake test site gave similar results and airborne propagation of carbon fibres was also studied here. Fibres were found 2 km from the test site. Carbon fibres released in a desert area were found to be still in suspension several miles away after a period of 3 years.

Work at the NASA Langley Research Centre suggests that single fibres could travel 100 km but fibre clusters with a higher fall rate might travel only about 10 km. Fibre lengths of 3 to 50 mm are possible.

The vulnerability of domestic electric appliances was noted in American work and a number of proposals are noted for the reduction of the carbon fibre hazard by modifying the fibres themselves.

UK experience is noted in this report. The Carbon Fibre Division of Courtaulds experienced short circuit problems in various types of electrical equipment. The problems were eliminated by protective covers and filtering the air. Both Courtaulds and Ciba-Geigy (UK) arrange to bury scrap materials to prevent accidental releases of fibre.

Work at RAE (Materials Department) showed that the burning of CFC laminates resulted in a limited releases of fibres mostly under 5 mm in length. Engineering Physics Department of RAE have concluded that airborne carbon fibres are unlikely to cause hazards to aircraft electrical systems because modern generators and their control and distribution systems are well shielded and insulated. Avionics systems (Flight Systems Department, RAE) and radio and navigation equipment (Radio and Navigation Department, RAE) are thought to be well protected against environmental hazards including airborne carbon fibres.

It is noted that the Central Electricity Generating Board Laboratories do not consider airborne carbon fibres to be a serious threat to electricity power supplies.

The conclusions suggest that the risks arising from an aircraft accident releasing carbon fibres are at the present time, fairly small. Nevertheless the risk of electrical hazards needs to be kept under review as the usage of CFC material increases. The possibility of the deliberate release of carbon fibres as an act of sabotage is pointed out.

A list of recommended procedures to follow after accidents to US aircraft containing carbon fibre composites is given as an appendix to thereport.

These procedures are taken from a guide, 'HAVE NAME', published in 1978.

139 Pridie, R.A : 'Environmental effects on composites for aircraft'. Report No NASA TM-78716, May 1978. NASA Langley Research Centre, Hampton, VA, USA.

Interim results from a number of on going long-term environmental effects programmes for composite materials are reported. The flight service experience was evaluated for 142 composite aircraft components after more than 5 years and 1 million successful component flight hours. Ground-based outdoor exposures of composite material samples after 3 years of exposure at 5 sites reached equilibrium levels of moisture pick-up which were predictable. Solar ultraviolet induced material loss is discussed for these same exposures. No significant degradation was observed in residual strength for either stressed or unstressed samples, or for exposures to aviation fuels and fluids.

140 Curtis, P.T : 'A basic computer programme to calculate moisture content in resins and fibre reinforced resin composites', RAE Technical Memo MAT 375.

A basic language computer programme is presented which calculates the moisture absorption of epoxy resin and fibre composite sheets from the sheet thickness, the diffusivity and the relative humidity of the environment. One-dimensional Fickian diffusion is assumed in the calculations. The programme gives the water absorbed by the material in a given exposure time,

together with the times for the material to absorb 95% and 99% of the maximum water uptake. In addition, the distribution of water through the laminate thickness is calculated and displayed graphically. The programme can be used for any resin or fibre composite in which the primary moisture diffusion mechanism is bulk diffusion through the resin. Examples for typical fibre reinforced epoxy composite laminates are given and the implications are discussed. Diffusion data for three materials at room temperature and two materials at 50°C are listed for use in the programme.

CHAPTER 12

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ABSTRACT The resistivity of small CFC samples at frequencies up to 300 MHz was measured using Q-meter techniques. Changes in resistance resulting from prolonged exposure to various liquids were investigated. Electromagnetic shielding (screening), 0.15-1000 MHz, was measured for CFC panels incorporated as one face of a cubic enclosure or as one surface panel of a helicopter tail cone and for a CFC cylinder. The performances of vhf and uhf aerials when mounted on metallic and CFC ground planes were compared. The implications of the results on the electromagnetic compatibility of CFC aircraft have been discussed and broad recommendations given. The report concludes with a survey of 140 published papers on the electrical and rf properties of CFC.

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